

# The Hubble Space Telescope GOODS NICMOS Survey: Overview and the Evolution of Massive Galaxies at $1.5 < z < 3$

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**ABSTRACT**

We present the details and early results from a deep near-Infrared survey utilising the NICMOS instrument on the *Hubble Space Telescope* centred around massive  $M_* > 10^{11} M_\odot$  galaxies at  $1.7 < z < 2.9$  found within the Great Observatories Origins Deep Survey (GOODS) fields North and South. The GOODS NICMOS Survey (GNS) was designed to obtain deep F160W (H-band) imaging of 80 of these massive galaxies, as well as other colour selected objects such as Lyman-break drop-outs, BzK objects, Distant Red Galaxies (DRGs), Extremely Red Objects (EROs), *Spitzer* Selected EROs, BX/BM galaxies, as well as flux selected sub-mm galaxies. We present in this paper details of the observations, our sample selection, as well as a description of features of the massive galaxies found within our survey fields. This includes: photometric redshifts, rest-frame colours, and stellar masses. We furthermore provide an analysis of the selection methods for finding massive galaxies at high redshifts, including colour selection methods and how galaxy populations selected through these colour methods overlap. We find that a single colour selection method cannot locate all of the massive galaxies, with no one method finding more than 70 percent. We however find that the combination of these colour methods finds nearly all the massive galaxies, as selected by photometric redshifts with the exception of apparently rare blue massive galaxies. By investigating the rest-frame ( $U - B$ ) vs.  $M_B$  diagram for these galaxies we furthermore show that there exists a bimodality in colour-magnitude space at  $z < 2$ , driven by stellar mass, such that the most massive galaxies are systematically red up to  $z \sim 2.5$ , while lower mass galaxies tend to be blue. We also discuss the number densities for galaxies with stellar masses  $M_* > 10^{11} M_\odot$ , whereby we find an increase of a factor of eight between  $z = 3$  and  $z = 1.5$ , demonstrating that this is an epoch when massive galaxies establish most of their mass. We also provide an overview of the evolutionary properties of these galaxies, such as their merger histories, and size evolution.

**Key words:** Galaxies: Evolution, Formation, Structure, Morphology, Classification

**1 INTRODUCTION**

Our understanding of distant galaxies and the history of galaxy formation has undergone a revolution in the past decade. Galaxies are now routinely discovered and studied out to redshifts  $z \sim 4 - 6$  (e.g., Dickinson et al. 2004; Yan et al. 2005; Bouwens et al. 2007; Bouwens et al. 2010). Samples of a few dozen objects have been found at even higher redshift, back to the era of reionization ( $z \sim 6 - 7$ ), and perhaps some galaxies have been discovered at even higher redshifts,  $z \sim 8 - 10$  (e.g., Bouwens et al. 2010; Finkelstein et al. 2010). This relatively rapid advance in our discovery of the earliest galaxies is the direct result of technical advances in spectroscopy and imaging over the past decade, in which the *Hubble Space Telescope* (*HST*) has played a leading role.

Historically, distant galaxies are found within deep optical imaging surveys, and are confirmed as high redshift galaxies with large multi-object spectrographs on 8-10 meter telescopes, which came online in the mid-1990s. It can be argued however that some of the most important advances in our understanding of galaxies has come about from very deep imaging, especially from *HST*. The *Hubble Space Telescope* has played a key role in high-redshift discoveries and our understanding of galaxy evolution through large blank field and targeted programs such as the *Hubble* Deep and Ultra Deep Fields, GOODS, EGS, and COSMOS, among

others (e.g., Williams et al. 1996; Giavalisco et al. 2004; Beckwith et al. 2006; Davis et al. 2007; Scoville et al. 2007).

This *Hubble* imaging has proven invaluable for two primary reasons. One is simply due to the depth that can be achieved with a high photometric fidelity, ensuring that exquisite photometry of distant galaxies can be obtained. Whilst ground based telescopes can reach the depths of *HST* at optical wavelengths, in principle the accuracy and precision of this photometry is not nearly as good, due to a higher background, and importantly, the large and variable PSF. This makes accurate measurements of light difficult, particularly for colours which require exact apertures for accurate measures. Furthermore, *HST* data have proven important for the discovery of the most distant galaxies in the Universe through the use of the Lyman-Break method of looking for drop-out galaxies in bluer bands. Many filter choices within multi-colour deep imaging programmes were in fact selected to facilitate optimal drop-out searches (e.g., Giavalisco et al. 2004).

*Hubble* imaging furthermore has facilitated a renaissance in the study of galaxy structure in the distant Universe, which provides a key observable for understanding how distant galaxies form and evolve (e.g., Conselice et al. 2003; Conselice et al. 2008, 2009; Lotz et al. 2008; Buitrago et al. 2008; Jogee et al. 2009; Bluck et al. 2009; Casatta et al. 2010). These structural measurements have proven critical for determining how galaxy morphologies, sizes, and merger/kinetic states have evolved through time (e.g., Trujillo et al. 2007; Ravindranath et al. 2004; Conselice et al.

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2003). This allows us to examine how the merger history of galaxies has changed (e.g., Conselice et al. 2003, 2008; Lotz et al. 2008; Jogee et al. 2009), and thus we can begin to derive how galaxies form, as opposed to simply when. It is not currently straightforward to measure the structures of distant galaxies with ground based imaging even with adaptive optics, and thus *Hubble* has and continues to provide a key aspect for tracing evolution using these methods.

However, one key aspect of parameter space that has not yet been explored with *HST*, or other space-based telescopes in any depth over large areas, is deep infrared imaging over a relatively large area. Previously there exists deep NIC3 imaging over the *Hubble* Deep Field (Dickinson et al. 2000) and Hubble Ultra-Deep Field (Thompson et al. 2004), as well as very deep NICMOS imaging over a small area of the HDF-N (Thompson et al. 1999). These areas are however very small, and while NIC3 parallel data exists over the COSMOS and EGS fields, it is quite shallow at  $\sim 1$  orbit depth. *HST* imaging data however has a distinct advantage over ground-based imaging not only in terms of the higher quality photometric fidelity and higher resolution, but also the depth which can be achieved in the near infrared (NIR) with *HST* – as opposed to the ground-based optical where comparable depths to *HST* can be reached. Within one or two orbits, the *HST* can reach a depth in the NIR which is difficult to obtain from the ground even with an 8-10-m class telescope, and which will not have the same photometric quality, nor resolution as the *Hubble* data.

We thus designed and carried out the GOODS NICMOS Survey (GNS), which is a large *HST* programme intended to remedy this situation by providing through an initial 180-orbit program of NIC3 imaging in the GOODS fields, a data set designed to examine a host of problems requiring very deep NIR data. The GNS data consist of 60 NICMOS NIC3 pointings, centred on the most massive ( $M_* > 10^{11} M_\odot$ ) galaxies at  $1.7 < z < 2.9$ . The depth of each image is 3 orbits/pointing within the  $H_{160}$ -bandpass over a total area of  $\sim 43 \text{ arcmin}^2$  (Buitrago et al. 2008; Bluck et al. 2009, Casey et al. 2009, Bouwens et al. 2009, 2010 present results using this data).

With these NICMOS data we are able to explore the rest-frame optical features of galaxies at  $z > 1$  in detail. This allows a few measurements to be made that cannot be easily reproduced with optical imaging and/or deep NIR imaging from the ground. This includes: filling in the important near-infrared gap in galaxy spectral energy distributions (SEDs); sampling the rest-frame optical structures and sizes of galaxies out to  $z \sim 3$  (Buitrago et al. 2008); and the detection and characterization of the population of massive  $z \sim 7 - 10$  galaxies and AGN, and determining the relation of AGN evolution to that of massive galaxies (e.g., Bluck et al. 2010).

In this paper we present the basic outline, background, and results from this survey. We discuss the design of the observations, our field selection, as well as the selection for our initial massive galaxy sample which has guided the centres for our NICMOS NIC3 pointings. We also discuss the various methods for locating the massive galaxy population at higher redshifts, and the connection of these massive galaxies to those at  $z < 2$ . We show that no one colour method is able to identify the massive galaxy population at high redshifts, and that a combination of methods and photometric

redshifts are needed to construct a semi-complete massive galaxy sample at higher redshifts. In this paper we construct as complete as possible sample of massive galaxies within our fields, and discuss the properties of these galaxies, as well as some features of lower mass galaxies.

This paper is organised as follows: §2 gives a summary of our observations and the design of the GNS, including how the initial sample of galaxies was selected. §3 gives a description of the derived parameters from the  $H_{160}$ -band imaging, including photometric redshifts and catalogue matching. §4 describes our initial analysis of the survey data, including how the various selections for massive galaxies at high redshifts compare, while finally §5 is our summary. We use a standard cosmology of  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , and  $\Omega_m = 1 - \Omega_\Lambda = 0.3$  throughout.

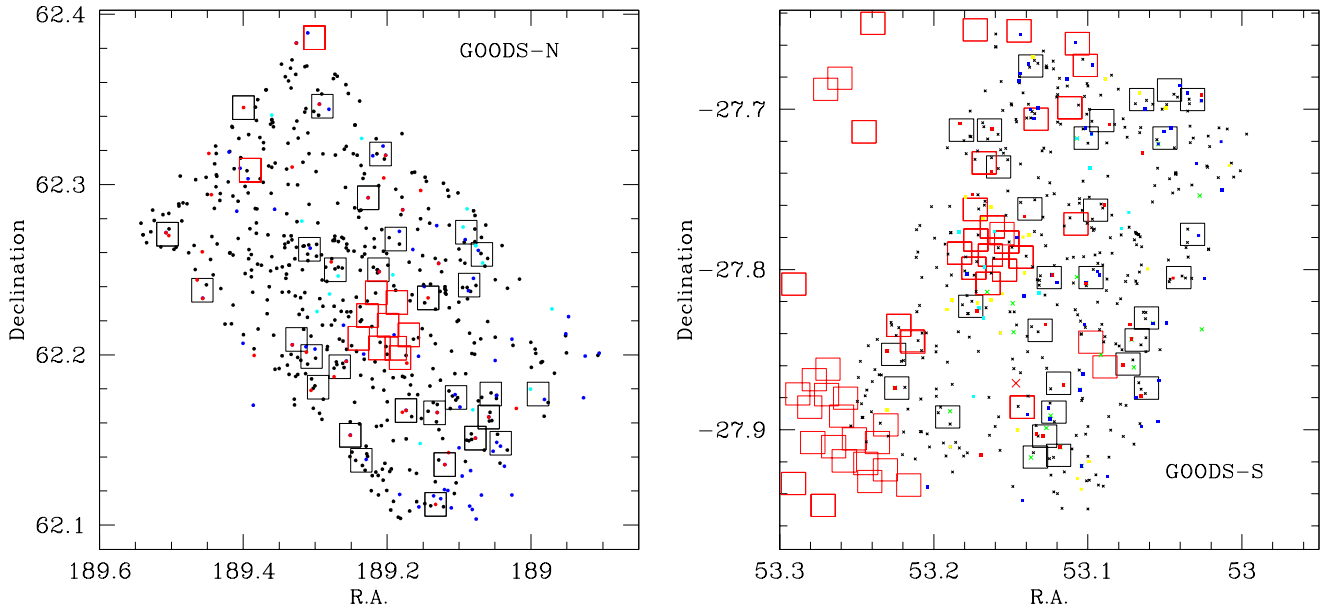
## 2 OBSERVATIONS

### 2.1 Survey Design

The GNS selection and field coverage is based on the previous optical ACS and ground-based imaging from the original GOODS program (Giavalisco et al. 2004). The GOODS programme is a multi-wavelength campaign to obtain a coherent collection of deep imaging and spectroscopy in two  $150 \text{ arcmin}^2$  areas in the northern and southern hemispheres (GOODS-N and GOODS-S). These two fields are centred around the *Hubble* Deep Field-North (HDF-N) and *Chandra* Deep Field-South (CDF-S), which are areas of very low dust extinction, and minimal stellar and radio contamination. The existing GOODS/ACS fields match the coverage of the GOODS *Spitzer* program and cover the 2 Msec exposure of the *Chandra* Deep Field South and the 2 Msec exposure of the *Chandra* Deep Field North (Luo et al. 2008). Large ongoing campaigns to obtain spectroscopy for the GOODS fields have also been carried out, including 3000 spectra as part of the Keck Treasury Redshift Survey (Wirth et al. 2004). Another  $\sim 3000$  redshifts in GOODS-S have been measured from various ESO programs (e.g., Vanzella et al. 2008; Le Fevre et al. 2005; Popesso et al. 2009; Balestra et al. 2010).

The co-moving volume probed by GOODS at high redshifts,  $2 < z < 6$ , is similar to the co-moving volume covered by the COSMOS field (e.g., Scoville et al. 2007) at  $0.2 < z < 1$ . Furthermore, due to its depth at all wavelengths the GOODS fields are thus an ideal location for examining the formation and evolution of early galaxies. Deep NIR imaging of these fields however is lacking, although some deep NIR imaging has been obtained with ESO telescopes using SOFI and ISAAC for the GOODS-South, as well as deep CFHT WIRCAM imaging, Subaru imaging, and some Keck imaging over the GOODS North (e.g., Kajisawa et al. 2009; Retzlaff et al. 2010; Wang et al. 2010). However, these data only reach modest depths of  $K_{\text{vega}} \sim 22$  compared to our *HST* imaging. The depth of our survey is only comparable to previous NICMOS deep programmes covering the HDF-North and HDF-South fields, as well as new near-IR data obtained with WFC3 (Cassata et al. 2010).

Ideally, one would want to cover both GOODS North fields completely, yet given the small NICMOS field of view it is not practical to cover the entire GOODS fields any deeper than one orbit with NICMOS. The WFC3 camera



**Figure 1.** The distribution of the global targets used within the GOODS North and South fields. The points displayed are: DRGs (green), IEROs (blue), BzKs (red), IRS *Spitzer* targets (cyan), V-drop outs (black), and high- $z$  galaxies with *Spitzer* IRS spectra (yellow). The black boxes show the locations of the GNS NICMOS pointings, while the red boxes are for previous deep NIC3 fields in these areas. The *Hubble* Deep Field (within GOODS North) and the *Hubble* Ultra Deep Field (within GOODS South) are shown in the centres of each field with overlapping red tiles. Note that these boxes have not been rotated to match the orientation of these fields.

will, however, soon cover these fields to an even great depth with the CANDELS programme. Our strategy is not to map out a continuous area, but to collect 60 pointed observations directed towards the most massive galaxies at  $z \sim 1.7 - 2.9$  found in the GOODS fields (§2.2), maximised to obtain the largest number of galaxies based on our selection methods. To obtain the most unique and useful science we therefore constructed a program which covers a sixth of the area of a single GOODS field (in total  $43.7 \text{ arcmin}^2$ ) in three orbits depth in the  $H_{160}$  band, in areas of the deepest *Spitzer*, *Chandra*, and ACS imaging, and where the greatest amount of spectroscopy already exists. Some of these fields were then observed in the  $J$ -band ( $J_{110}$ ) with NICMOS or WFC3 as part of a follow up programme to obtain near infrared SEDs to look for high redshift drop-out galaxies (Bouwens et al. 2010).

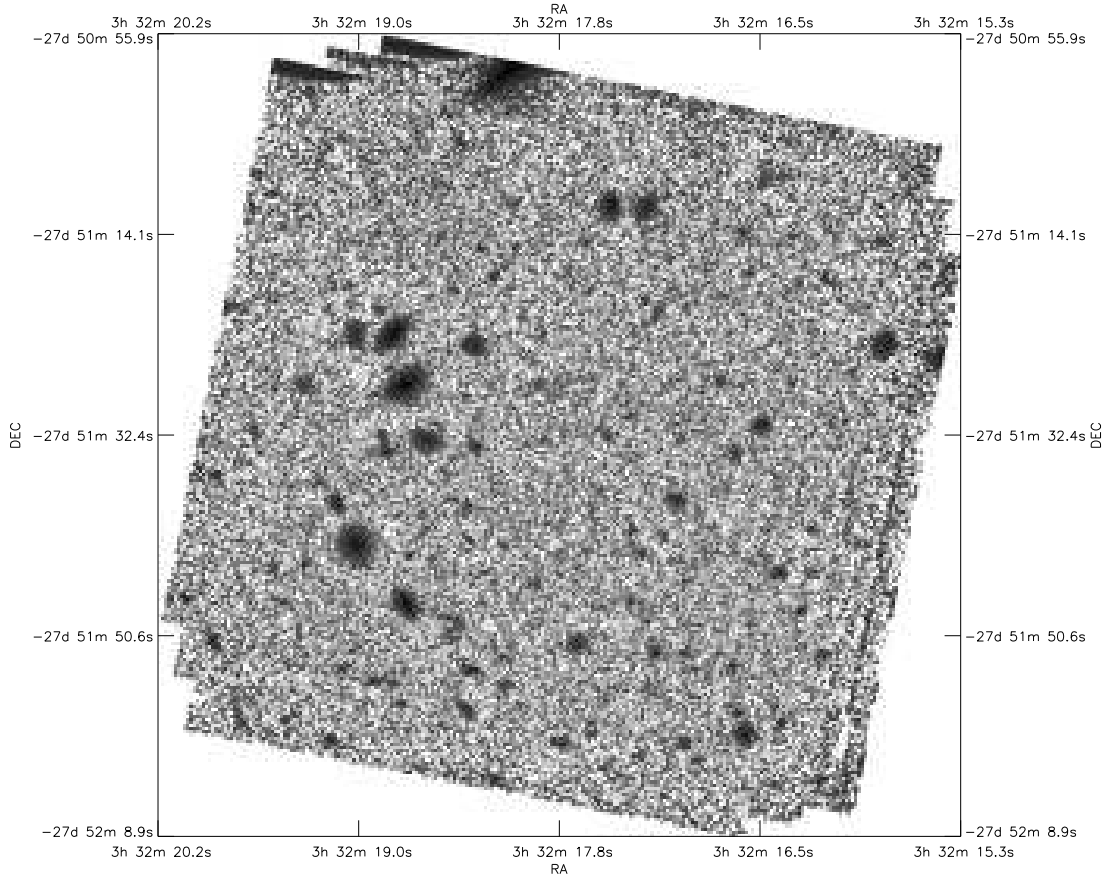
## 2.2 Initial Galaxy Selection

Our NICMOS pointings were chosen to target a set of objects selected to be known massive galaxies at high redshift, identified using a variety of color selection methods. These include “Distant Red Galaxies” (DRG: Franx et al. 2003; Papovich et al. 2006), IRAC Extremely Red Objects (Yan et al. 2006), and BzK color-selected galaxies (Daddi et al. 2004, 2007). All of these methods are designed to find red, dusty or passively evolving older galaxies at  $z > 1.5$ . In

practice, we utilised all three of these colour-selections separately, in order to obtain as much as possible a complete sample of massive galaxies at  $z > 2$ . To optimise our field placement, we also used catalogues of Lyman-break selected BM/BX objects (Reddy et al. 2008), as well as high redshift drop-outs and sub-mm galaxies. However, the primary field selection was done in terms of the massive galaxy selection through the three primary colour criteria as described further below.

Colour selection of distant galaxies has a long history dating back to the early work of finding Lyman-break galaxies through image drop-outs in blue bands (e.g., Guhathakurta, Tyson, Majewski 1990; Steidel & Hamilton 1992). It is generally accepted that no single method can find all galaxies at a given redshift, and some of these methods are better at finding star-forming objects, as opposed to those which are more passive and evolved. In fact, it is generally agreed that no method or combination of methods can identify an obviously complete sample of high- $z$  galaxies.

One of the methods we use for finding likely passively evolving and dusty red galaxies is to find Distant Red Galaxies (DRGs) defined by a NIR colour cut (e.g., Franx et al. 2003; Papovich et al. 2006; Conselice et al. 2007b). The selection we use to find DRGs, and to be included within our sample, is galaxies at  $z \sim 1.7 - 2.9$  with  $(J - K_s) > 2.3 \text{ mag}$  in Vega magnitudes (or  $> 1.37$  in AB mags). The selection for these galaxies is based on ground-based imaging from



**Figure 2.** Example of one of our NICMOS images in the  $H_{160}$  band. This example is for GOODS-South 16. The field of view of this and all the NICMOS pointings is approximately 51 arcsec on a side.

ISAAC on the Very Large Telescope (VLT). This selection is only used for choosing systems in GOODS-S, as deep NIR imaging over the entire GOODS-N field was not available when the target selection was carried out. This GOODS-S DRG sample is approximately complete for  $M_* > 10^{11} M_\odot$  DRG selected galaxies at  $z < 3$  (Papovich et al. 2006).

Another selection we use to construct our initial massive sample is the *Spitzer* selected extremely red objects (EROs), otherwise known as Infrared EROs (IEROs). These were first described in Yan et al. (2004), based on NIR and *Spitzer* data within the GOODS fields. The selection for these objects is  $S_\nu(3.6 \mu\text{m})/S_\nu(0.9 \mu\text{m}) > 20$ . These objects were found by Yan et al. (2004), based on SED fits, to have a mixture of old and younger populations. Note that selecting galaxies in this way ensures that they are massive given their brightness in the IR. However, because they are selected with *Spitzer* imaging, which has a large PSF, resulting in potential confusion from neighboring objects, this selection can have issues with contamination from other galaxies. Hence any galaxies which would satisfy the criteria but are too close to another galaxy will not be included simply due to the problem of confusion.

Another method we use to select distant galaxies is through the BzK approach, which is described in Daddi et al. (2007) in terms of selection within the GOODS fields. The selection for these objects is slightly more complicated than

that of the DRGs or IEROs, since they are selected through colours using the  $B$ ,  $z$  and  $K$ -bands together. This method proposes to separate evolved galaxies or passive pBzKs, and those which are star forming, or sBzKs. The selection for these galaxies is done through the quantity  $BzK$ , defined using these three bands by:

$$BzK = (z - K)_{AB} - (B - z)_{AB}. \quad (1)$$

Star forming galaxies at  $z > 1.4$  are proposed to have  $BzK > -0.2$ . The redder, possibly more evolved galaxies, are found through the selection  $BzK < -0.2$  and  $(z - K)_{AB} > 2.5$ . For the BzK sample we use, the selection is somewhat more limited than for the other colour selections as these sources were selected down to  $K = 20.5$  Vega in the North and  $K = 22$  in the South. We utilise photometric redshifts and stellar masses of the galaxies selected through these methods to identify and study these colour selected populations taken directly from Papovich et al. (2006), Yan et al. (2004) and Daddi et al. (2007).

Our initial massive galaxy sample from which we optimise our NICMOS pointings are selected through these three methods, with a further photometric redshift cut of  $1.7 < z < 2.9$ , and with a stellar mass cut of  $M_* > 10^{11} M_\odot$ . In practice our final pointings were chosen by finding the locations within the GOODS fields where the number of these massive galaxies was maximised within the NIC3

fields. In total we imaged 45 pre-selected massive  $M_* > 10^{11} M_\odot$  galaxies at  $1.7 < z < 2.9$  in the GOODS-N, and 35 in the GOODS-S.

Galaxies selected in other ways were also used to optimise the number of galaxies in each NIC3 pointing, although each pointing was designed to have at least one massive galaxy with the properties above. These ‘additional’ galaxies are selected through the Lyman-break drop-out method utilising  $B$ ,  $V$  and  $i$  drop-outs, the BX/BM selection, as well as sub-mm galaxies from Greve et al. (2008). Each NIC3 pointing contained between four to 19 of each of these galaxy types. Figure 1 shows our field layout within the GOODS fields with the different galaxy types shown as different colours and symbols, and Figure 2 shows a typical NICMOS NIC3 pointing of one of our fields.

Tables 1 and 2 list the statistics and positions of our 60 pointings, with 30 NIC3 pointings in the GOODS-North field, and 30 in GOODS-South. We also list the number of various other types of galaxies within each of these fields. Tables 3 and 4 list the initial massive galaxies for which we picked our fields, along with basic information such as their photometric redshifts, stellar masses, and information on the optical and  $H_{160}$ -band magnitudes for these systems. NICMOS and ACS images of ten of these massive galaxies are shown in Figure 3. This data, including catalogs of sources, redshifts and stellar masses, as well as the original reduced NIC3 imaging itself is available at <http://www.nottingham.ac.uk/astronomy/gns/>.

### 2.3 Observational Parameters and Data Reduction

For our observations, we used the NIC3 camera in the  $H$ (F160W) ( $H_{160}$ ) band, with a depth of 3 orbits per pointing. With this exposure time we predicted that we would reach  $H_{160} = 26.5$  (AB) at  $5\sigma$  for an extended source within a 0.7 arcsec diameter. This imaging, combined with ground-based data at a similar depth, is optimal for measuring photometric redshifts at  $z \sim 2$ , where the Balmer break occurs for galaxies at these redshifts, and for finding  $z$ -band drop-outs ( $z > 6$ ) as candidate high- $z$  galaxies (Bouwens et al. 2010).

Our data were processed with the NICMOS reduction package `NICRED.py` v1.0. A detailed description of this package can be found in Magee, Bouwens, & Illingworth (2007). `NICRED` v1.0 handles all pipeline processing steps currently recommended by STScI for NICMOS data. Basic calibration, including zero read correction, bad pixel masking, noise calculation, dark current subtraction, linearity correction, flat field correction, photometric calibration, and cosmic ray identification, was handled with the IRAF task `CALNICA`. Pedestal removal and bias subtraction was performed with the IRAF task `PEDSKY`.

The NICMOS data was taken with three dithers per orbit using a point spacing of 5.06, for a total of nine dithers, which was then used to drizzle the data into the final prod-

uct. Exposure times are roughly 8100 seconds per target in the F160W band. Each exposure was cleaned of any South Atlantic Anomaly signatures using the algorithm of Bergeron & Dickinson (2003, ISR), as implemented in the STScI-Python task `saaclean.py`. Correction for the “Mr. Staypuft” anomaly was also made using a python task equivalent to STScI-python task `puftcorr.py`.

To improve the overall flatness of individual frames, we median-stacked all of the frames associated with the program (after masking out individual sources) to create a super median frame. We then subtracted this median from each of the individual exposures. Each exposure was also corrected for the NICMOS count rate non-linearity as identified by Bohlin et al. (2005) and later more thoroughly characterized by de Jong et al. (2006). This latter correction was made using the python task `nonlincor.py`.

Because our NICMOS images were taken in a single visit, we did not attempt to correct the relative astrometry of the individual frames to improve the overall alignment solution, although we did adjust the astrometry by  $0.3''$  in declination when aligning with the GOODS ACS v2.0 imaging. In preparation for the final image combination process, inverse weight maps were computed for each exposure based upon their individual exposure times, the reference darks, and flat fields. Finally, the individual exposures were combined into a final rectified frame with `multidrizzle`, rejecting any pixel in an exposure that was more than  $4\sigma$  away from the median defined by the stack. We used a threshold of  $3.5\sigma$  for the rejection threshold for pixels adjacent to an already rejected pixel.

We calculated that zero-points for the  $H_{160}$  images are 25.17 AB mag, and include a correction for the NICMOS non-linearity count rate<sup>1</sup>. In total we obtained 60 pointings for our observations, each one roughly centred on a massive galaxy at  $z = 1.7 - 2.9$ . The field of view of each of these images is 51.2 arcsec on a side with a subsampled pixel scale for the final drizzled mosaics of  $0.1 \text{ arcsec pixel}^{-1}$ . We measure that the FWHM for our images is roughly 0.3 arcsec.

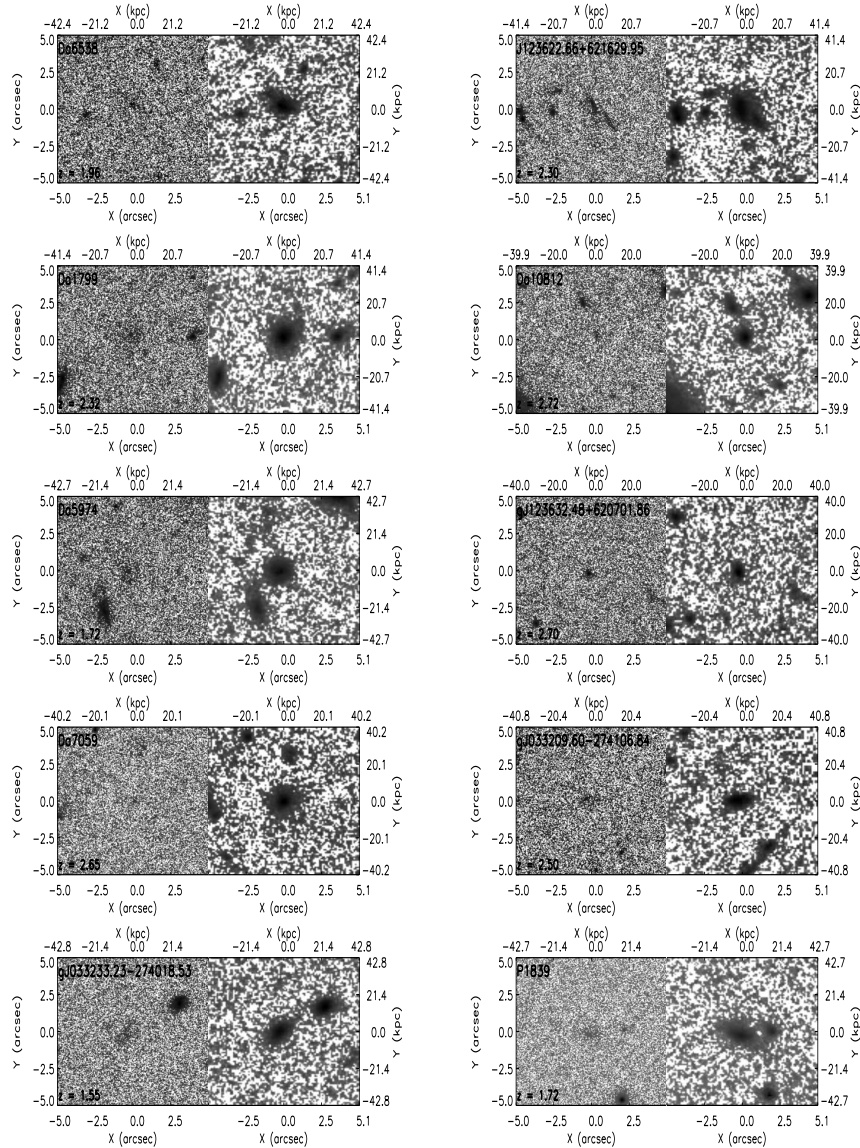
The depth of our data was determined by placing random apertures throughout the images and determining what fraction of simulated sources can be retrieved, and by measuring the RMS noise at various positions in the imaging. Using this method we find that the depth at the  $5\sigma$  limit is 26.8 AB mag using a 0.7 arcsec-diameter aperture. This is similar to our initial estimate based on the depth of our imaging.

### 2.4 SExtractor Detections and Photometry

After our images were reduced to their three orbit depths we then carried out image detection and photometry with the `SExtractor` package. This is now a standard method for detecting galaxies within imaging, and we only give a brief overview of the methods which we used. The photometry was also done within `SExtractor`, both for total magnitudes as well as magnitudes measured with a series of apertures.

The basic idea behind `SExtractor` is to detect objects

<sup>1</sup> This zero point differs from that given in the headers of the NICMOS data themselves, because the imaging data are expressed in electrons  $s^{-1}$  rather than  $DN \text{ s}^{-1}$ , with a gain of 6.5.



**Figure 3.** Montage of example GNS massive galaxies with  $M_* > 10^{11} M_\odot$ . Shown on the left-hand side of each image is the galaxy in the ACS  $z$ -band, while the right hand side shows the NICMOS NIC3  $H_{160}$ -band view of the same galaxy. The sizes in kpc is on the top and in arcsec on the bottom.

within an astronomical image and to carry out basic analyses of the photometry and shapes of these objects, typically galaxies and stars. Using SExtractor on an interactive basis we were able to find an optimal detection and deblending method that accounted for nearly all objects that can be identified as separate galaxies and stars by eye. Weight maps of the exposure times were used within the detection procedure. Overall we find a total of 8298 galaxies within our SExtracting and cleaning process.

We constructed, an optically matched catalogue of ACS imaging in the  $BVi$  bands based on the positions of the galaxies in the NICMOS catalog. Photometry in  $B$ ,  $V$ ,  $i$  and  $z$  bands are available for sources down to a  $5\sigma$  limiting AB magnitude of  $z \sim 27.5$  from the original ACS GOODS survey (Giavalisco et al. 2004) using v2.0 data products. We used the positions of objects in our NICMOS catalogue to match with  $BVi$  photometry from the ACS v2.0 data. We used AUTOMAG magnitudes to measure the magnitudes

**Table 1.** The GOODS-N NICMOS Fields with numbers of galaxies of different types

| ID | RA(J2000)  | Dec (J2000) | V-drops | i-drops | IEROs | BzK | sub-mm | BX/BM | Other | Total |
|----|------------|-------------|---------|---------|-------|-----|--------|-------|-------|-------|
| 1  | 12 36 31.8 | 62 06 43.7  | 2       | 1       | 4     | 1   | 1      | 0     | 0     | 9     |
| 2  | 12 36 28.8 | 62 08 07.8  | 1       | 1       | 3     | 1   | 0      | 0     | 0     | 6     |
| 3  | 12 36 14.1 | 62 09 48.5  | 3       | 0       | 5     | 1   | 0      | 0     | 0     | 9     |
| 4  | 12 36 18.5 | 62 09 03.7  | 4       | 0       | 2     | 1   | 0      | 0     | 0     | 7     |
| 5  | 12 37 00.3 | 62 09 09.8  | 0       | 0       | 1     | 1   | 0      | 2     | 0     | 4     |
| 6  | 12 36 41.7 | 62 10 02.3  | 1       | 0       | 3     | 2   | 0      | 1     | 1     | 8     |
| 7  | 12 36 34.3 | 62 14 00.4  | 1       | 0       | 0     | 1   | 1      | 2     | 1     | 6     |
| 8  | 12 38 01.3 | 62 16 15.2  | 1       | 0       | 3     | 2   | 1      | 0     | 0     | 7     |
| 9  | 12 36 54.3 | 62 17 31.9  | 0       | 0       | 1     | 1   | 0      | 2     | 0     | 4     |
| 10 | 12 37 35.9 | 62 20 42.9  | 0       | 0       | 2     | 1   | 0      | 0     | 0     | 3     |
| 11 | 12 37 11.0 | 62 10 51.6  | 3       | 0       | 3     | 1   | 1      | 8     | 0     | 16    |
| 12 | 12 37 03.8 | 62 11 34.8  | 5       | 2       | 2     | 2   | 0      | 4     | 1     | 16    |
| 13 | 12 36 16.3 | 62 15 32.4  | 2       | 1       | 3     | 0   | 1      | 5     | 3     | 15    |
| 14 | 12 37 05.3 | 62 15 00.0  | 5       | 0       | 0     | 1   | 0      | 4     | 2     | 12    |
| 15 | 12 37 13.2 | 62 11 56.4  | 2       | 0       | 3     | 1   | 1      | 3     | 1     | 11    |
| 16 | 12 37 13.9 | 62 15 43.2  | 7       | 0       | 1     | 0   | 0      | 3     | 1     | 12    |
| 17 | 12 36 13.4 | 62 10 37.2  | 4       | 0       | 3     | 0   | 1      | 2     | 0     | 10    |
| 18 | 12 36 50.9 | 62 15 00.0  | 5       | 1       | 2     | 1   | 0      | 1     | 3     | 13    |
| 19 | 12 36 10.1 | 62 08 52.8  | 2       | 0       | 7     | 0   | 1      | 0     | 0     | 10    |
| 20 | 12 36 21.6 | 62 16 19.2  | 2       | 0       | 3     | 0   | 0      | 1     | 1     | 7     |
| 21 | 12 36 20.6 | 62 14 27.6  | 4       | 0       | 3     | 0   | 0      | 2     | 1     | 10    |
| 22 | 12 36 32.2 | 62 09 57.6  | 4       | 0       | 4     | 1   | 0      | 1     | 0     | 10    |
| 23 | 12 36 56.6 | 62 08 16.8  | 5       | 1       | 1     | 0   | 0      | 2     | 0     | 9     |
| 24 | 12 37 09.6 | 62 20 45.6  | 2       | 0       | 3     | 1   | 1      | 1     | 2     | 10    |
| 25 | 12 36 25.0 | 62 10 30.0  | 4       | 0       | 5     | 0   | 0      | 0     | 0     | 9     |
| 26 | 12 36 45.1 | 62 16 04.8  | 2       | 0       | 2     | 0   | 0      | 5     | 0     | 9     |
| 27 | 12 36 50.2 | 62 19 04.8  | 2       | 0       | 3     | 1   | 1      | 0     | 1     | 8     |
| 28 | 12 37 18.2 | 62 12 32.4  | 0       | 0       | 1     | 1   | 0      | 5     | 1     | 8     |
| 29 | 12 37 49.7 | 62 14 16.8  | 1       | 0       | 3     | 2   | 1      | 0     | 0     | 7     |
| 30 | 12 35 57.6 | 62 10 39.4  | 0       | 1       | 2     | 0   | 0      | 0     | 1     | 4     |

Notes. Listed are the centre positions of each NIC3 pointing for the GNS in terms of RA and Dec. Also listed are the number of V-drops, i-drops, IEROs, BzKs and DRGs. Note that the colour selected types listed here are not just galaxies with  $M_* > 10^{11} M_\odot$ , but all galaxies that meet the criteria outlined in Section 2. We also include an ‘Other’ column which includes the total summation of: sub-mm galaxies, galaxies with *Spitzer* infrared spectrograph coverage, and BM/BX galaxies from Reddy et al. (2008). The total number of galaxies we used to pick these fields is also shown.

for both the  $H$ -band and the  $BViz$  magnitudes, which accounts for the total amount of light within each galaxy at every wavelength. We used these magnitudes to obtain  $BVizH$  spectral energy distributions for every source. These SEDs are used for colour measurements as well as for SED fitting for photometric redshifts and stellar mass calculations. A large fraction of our sources, 1219 out of 8298, have no counterpart in the  $z$ -band down to our limit of  $z_{850} = 27.5$ .

After accounting for a well-known  $0.3''$  offset in the declination direction between the NICMOS and ACS v2.0 data, we find that the average offset between the ACS positions and the NICMOS sources they are identified with is  $0.06 \pm 0.04''$ . We then later use this optical and NIR matched catalog to derive properties such as photometric redshifts as well as stellar masses for each of our galaxies. This also allows for us to search for drop-out galaxies which may be at ultra-high redshift (Bouwens et al. 2010).

We decided to only use *HST* imaging for our photometric catalogue when calculating redshifts and stellar masses to ensure a high fidelity in our photometry. While the GOODS fields have imaging at many ground-based wavelengths (Gialalisco et al. 2004), this imaging is often at a similar wavelength range to an ACS+NICMOS catalog, with the excep-

tion of a few pass-bands, such as the  $U$ -band and  $K$ -band. The accuracy of our matched photometry is very high, and our depth much greater than this ground based imaging, and thus to obtain a cleaner measurement we have limited our analysis to these five bands. Furthermore, we do not use *Spitzer* IRAC photometry for our galaxies (although we have matched these) simply because of issues due to contamination and deblending which can be substantial for galaxies which are separated by less than the PSF of the IRAC imaging (several arcsec in FWHM), making measurements of our photometry and stellar masses much more difficult.

#### 2.4.1 Number Counts

In Figure 4 we present the number counts for our  $H_{160}$ -band imaging, with a comparison to counts from the *Hubble* Deep Field South (Metcalf et al. 2006) and the HDF-N (Thompson et al. 1999). Based on a comparison to these  $H_{160}$  counts, we are roughly complete in our galaxy selection to roughly  $H_{160} = 25.5$ . The scatter in the counts at the faint end are most certainly due to cosmic variance effects, given the small field of view of these previous surveys. There are, however, some differences, particularly at the faint end of the counts,

**Table 2.** The GOODS-S NICMOS Fields with numbers of galaxies of different types

| ID | RA (J2000) | Dec (J2000) | V-drops | i-drops | IEROs | BzK | DRGs | Other | Total |
|----|------------|-------------|---------|---------|-------|-----|------|-------|-------|
| 1  | 03 32 23.5 | −27 48 18.0 | 3       | 2       | 5     | 1   | 5    | 0     | 16    |
| 2  | 03 32 24.2 | −27 43 04.8 | 2       | 1       | 8     | 0   | 2    | 3     | 16    |
| 3  | 03 32 22.8 | −27 45 46.8 | 3       | 2       | 4     | 1   | 3    | 0     | 13    |
| 4  | 03 32 30.0 | −27 48 18.0 | 2       | 1       | 6     | 1   | 2    | 1     | 13    |
| 5  | 03 32 42.2 | −27 49 22.8 | 4       | 1       | 2     | 1   | 0    | 2     | 10    |
| 6  | 03 32 54.2 | −27 51 10.8 | 2       | 0       | 8     | 1   | 2    | 0     | 13    |
| 7  | 03 32 15.6 | −27 41 38.4 | 3       | 1       | 4     | 0   | 2    | 1     | 11    |
| 8  | 03 32 21.8 | −27 42 25.2 | 1       | 0       | 3     | 1   | 1    | 0     | 6     |
| 9  | 03 32 29.3 | −27 53 20.4 | 2       | 0       | 5     | 0   | 3    | 0     | 10    |
| 10 | 03 32 30.7 | −27 54 14.4 | 1       | 0       | 3     | 2   | 4    | 0     | 10    |
| 11 | 03 32 45.8 | −27 53 31.2 | 2       | 0       | 4     | 0   | 3    | 0     | 9     |
| 12 | 03 32 53.8 | −27 52 26.4 | 2       | 0       | 3     | 1   | 3    | 0     | 9     |
| 13 | 03 32 12.0 | −27 43 04.8 | 1       | 0       | 4     | 0   | 3    | 0     | 8     |
| 14 | 03 32 14.9 | −27 52 26.4 | 3       | 0       | 3     | 1   | 1    | 0     | 8     |
| 15 | 03 32 16.3 | −27 50 38.4 | 3       | 1       | 3     | 1   | 1    | 0     | 9     |
| 16 | 03 32 17.8 | −27 51 32.4 | 1       | 0       | 3     | 1   | 3    | 0     | 8     |
| 17 | 03 32 32.9 | −27 40 22.8 | 3       | 2       | 2     | 0   | 0    | 1     | 8     |
| 18 | 03 32 07.7 | −27 41 38.4 | 3       | 0       | 3     | 1   | 0    | 0     | 7     |
| 19 | 03 32 09.8 | −27 48 18.1 | 4       | 1       | 2     | 1   | 0    | 0     | 8     |
| 20 | 03 32 11.3 | −27 41 16.8 | 2       | 0       | 6     | 0   | 0    | 0     | 8     |
| 21 | 03 32 14.9 | −27 49 49.1 | 3       | 1       | 2     | 0   | 1    | 0     | 7     |
| 22 | 03 32 28.6 | −27 54 57.6 | 2       | 1       | 2     | 1   | 1    | 0     | 7     |
| 23 | 03 32 28.6 | −27 52 15.6 | 1       | 2       | 2     | 1   | 2    | 0     | 8     |
| 24 | 03 32 31.4 | −27 50 16.8 | 2       | 1       | 3     | 1   | 0    | 0     | 7     |
| 25 | 03 32 24.2 | −27 55 34.7 | 3       | 1       | 2     | 0   | 1    | 2     | 9     |
| 26 | 03 32 43.7 | −27 42 46.8 | 3       | 0       | 3     | 1   | 0    | 0     | 7     |
| 27 | 03 32 32.2 | −27 55 01.2 | 1       | 0       | 1     | 2   | 0    | 0     | 4     |
| 28 | 03 32 07.7 | −27 46 40.8 | 2       | 3       | 2     | 0   | 0    | 0     | 7     |
| 29 | 03 32 33.0 | −27 45 43.9 | 2       | 0       | 1     | 1   | 1    | 0     | 5     |
| 30 | 03 32 39.3 | −27 42 48.3 | 4       | 2       | 0     | 1   | 1    | 0     | 8     |

Notes. Listed are the centre positions of each NIC3 pointing for the GNS in terms of RA and Dec. Also listed are the number of V-drops, i-drops, IEROs, BzKs and DRGs. Note that the colour selected types listed here are not just galaxies with  $M_* > 10^{11} M_\odot$ , but all galaxies that meet the criteria outlined in Section 2. We also include an ‘Other’ column which includes the total summation of: sub-mm galaxies, galaxies with *Spitzer* infrared spectrograph coverage, and BM/BX galaxies from Reddy et al. (2008). The total number of galaxies we used to pick these fields is also shown.

which can also be seen by comparing the HDF-S and HDF-N counts. This shows that we are obtaining similar photometric quality to these previous deeper NICMOS pointings and our reduction and detection processes are consistent with previous work.

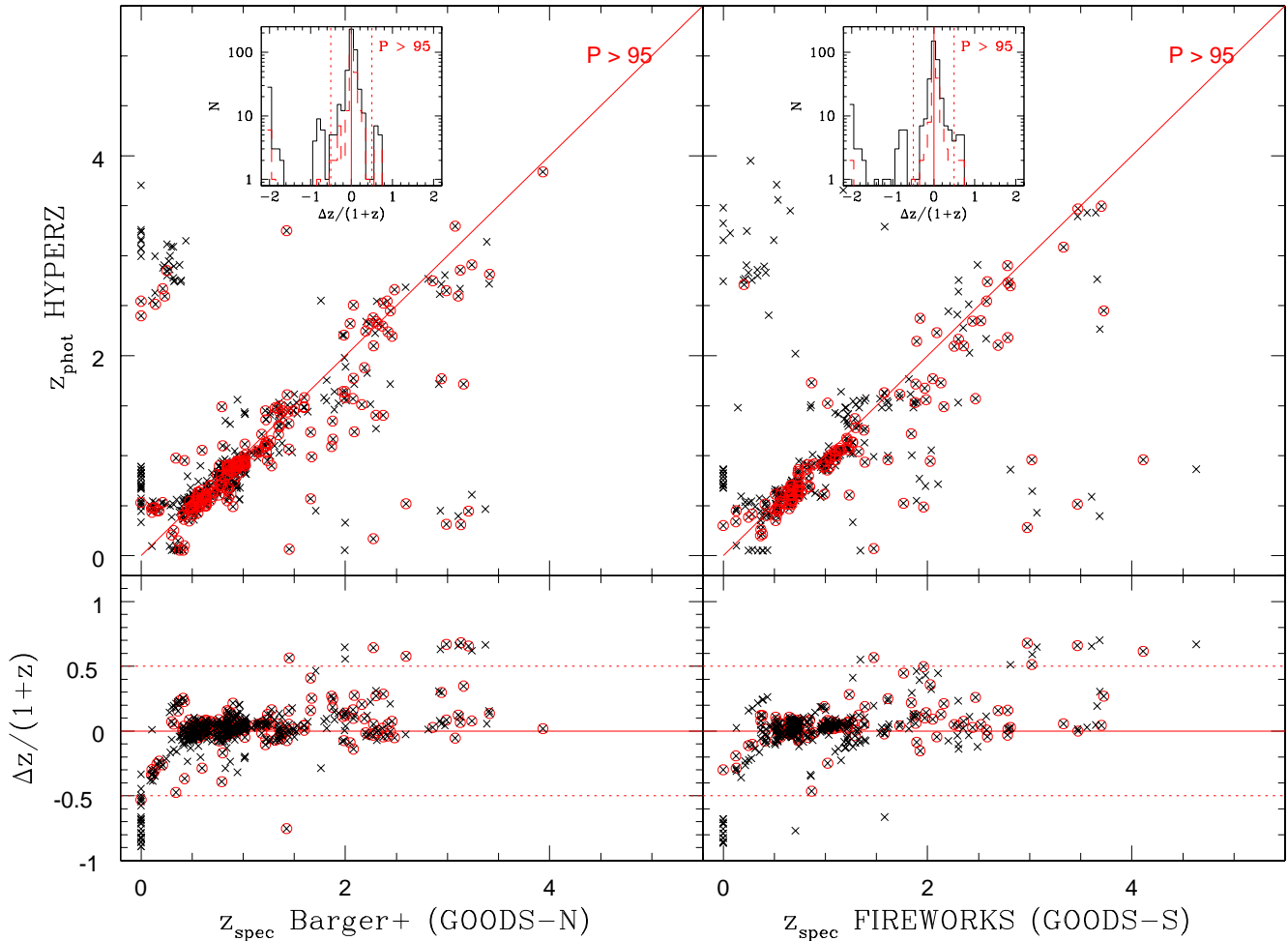
### 3 DERIVED PARAMETERS

There are two primary catalogues used within the GNS. The first is the initial catalogue of massive galaxies, selected by the methods described in §2.2. The other is the SExtractor based catalog of the survey based on the  $H_{160}$ -band imaging. This catalogue is an  $H_{160}$ -band catalogue of every object which is imaged within the NIC3 survey, regardless of mass and brightness. These two catalogues will be used for different purposes throughout this study, and in the follow-up papers, with detailed analyses of various aspects of this work. We describe in this section the redshift and stellar mass data we use to construct the first sample from which our initial targets were chosen. We also describe in detail the redshifts and stellar masses derived from the new optical+NIR catalog which we constructed using our  $H_{160}$ -band selected objects matched to the optical ACS photometry.

#### 3.1 Photometric Redshift Measurements

To obtain photometric redshifts, the NICMOS  $H_{160}$  band sources are matched to the catalogue of optical sources in the GOODS-ACS fields as described in §2.4. Photometric redshifts are then obtained by fitting template spectra to the  $BVIzH$  photometric data points. We do not include other wave-bands or ground-based data; we omit these so that we can obtain the highest fidelity photometry not affected by zero-point random and systematic errors, background noise, or confusion with other sources, as described in §2.3. The degeneracy in color-redshift space is problematic, especially when few filters are available. To cope with this effect we used two different approaches: the standard  $\chi^2$  minimisation procedure, using *HYPERZ* (Bolzonella et al. 2000), and a Bayesian approach using the *BPZ* method (Benitez 2000).

The synthetic spectra used by *HYPERZ* are constructed with the Bruzual & Charlot (2003; BC03) evolutionary code, representing roughly the different types of galaxies found in the local Universe. We use five template spectra corresponding to the spectral types of: E, Sa, Sc and Im, as well as a single star burst model. The reddening law is taken from Calzetti et al. (2000). The code then computes the most likely redshift solution in the parameter space of age, metal-



**Figure 5.** Reliability of photometric redshifts: *Top panels:* photometric vs. spectroscopic redshifts in the GOODS-N (left) and GOODS-S (right) fields for galaxies with redshift probabilities ( $P$ ) greater than 95 percent. The insets show the distribution of  $\Delta z/(1+z)$  for all photometric redshifts (black) and high probability redshifts only (red, long dashed). *Bottom panels:*  $\Delta z/(1+z)$  dependence on redshift. Black symbols show all redshifts, red symbols high probability redshifts only. The dashed lines in all the panels and subpanels, show a limit for catastrophic outliers at  $|\Delta z/(1+z)| > 0.5$ .

licity, and reddening. The best fit redshift and corresponding probability are then output together with the best fit parameters of spectral type, age, metallicity,  $A_V$  and secondary solutions of these.

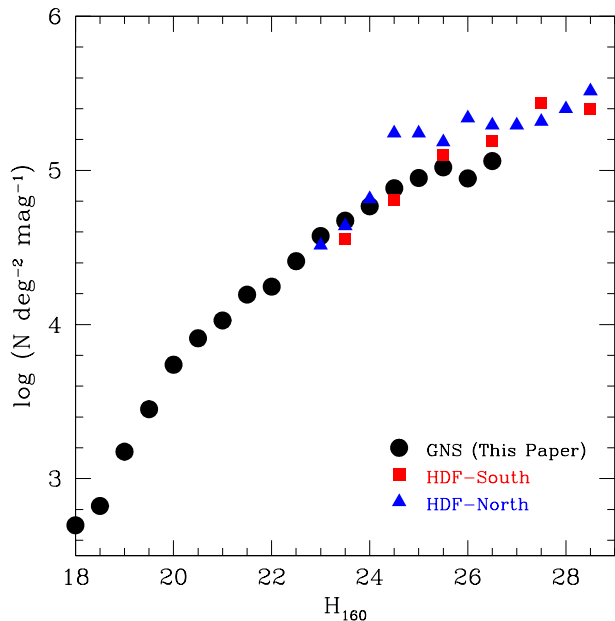
The Bayesian approach of Benitez (2000) uses a similar template fitting method, as well as using an empirical rather than synthetic template SEDs. The main difference from *HYPERZ* is that it does not rely on the maximum likelihood of the redshift solution in the parameter space as described above. Instead it uses additional empirical information about the likelihood of a certain combination of parameters, also known as prior information, or priors. The redshift solution with the maximum likelihood is determined after weighting the probability of each solution by the additional probability determined from the prior information. In our case the prior is the distribution of magnitudes for different morphological types as a function of redshift, obtained from *Hubble* Deep Field North (HDF-N) data (Benitez 2000). In short, the code not only determines the best fit redshift and spectral type, but also takes into account how likely is it to find a galaxy of that spectral type and magnitude at the given redshift.

### 3.2 Comparison with Spectroscopic Redshifts

Since the spectroscopic redshifts of sources in the two GOODS fields (North and South) were taken from different compilations of data, we compare them separately to the photometric redshifts from their respective fields in this section.

Spectroscopic redshifts of sources in the GOODS-N field were compiled by Barger et al. (2008), whereas in the GOODS-S field spectroscopic redshifts are taken from the FIREWORKS compilation (Wuyts et al. 2008). We matched these catalogues to our photometric catalogue, obtaining 537 spectroscopic redshifts for our sources in GOODS-N and 369 in GOODS-S. The mean separation between photometric and spectroscopic sources is  $0.41 \pm 0.06$  arcsec in the GOODS-N field and  $0.13 \pm 0.05$  arcsec in the GOODS-S field.

The reliability of photometric redshift measures is often defined by  $\Delta z/(1+z) \equiv (z_{\text{spec}} - z_{\text{phot}})/(1+z_{\text{spec}})$ . In the following we compare the median error ( $\langle \Delta z/(1+z) \rangle$ ) and rms scatter ( $\sigma$ ) as well as the fraction of catastrophic out-



**Figure 4.** Number counts within our GNS  $H_{160}$  band imaging. Shown for comparison are number counts from the HDF-North and HDF-South imaging which were taken using the same camera and filter. Data for the *Hubble* Deep Field (HDF) South originates from Metcalfe et al. (2006) and the the HDF-N number counts are from Thompson et al. (1999).

liers, i.e., galaxies with both  $|\Delta z/(1+z)| > 0.5$  and  $> 0.2$ , obtained by the two methods described above.

We find good agreement between photometric and spectroscopic redshifts for both codes. However, *HYPERZ* gives slightly better results, although *BPZ* gives more high probability ( $P$ ) redshifts. Using *HYPERZ*, we obtain the following results: sources in the GOODS-N field have an  $\langle \Delta z/(1+z) \rangle = 0.027$ , with a scatter of  $\sigma = 0.04$  (222 out of 537 galaxies with  $P > 95$  percent). Sources in the GOODS-S field show similar values:  $\langle \Delta z/(1+z) \rangle = 0.043$  and  $\sigma = 0.04$  (134 of 369 with  $P > 95$  percent). *BPZ* gives slightly higher errors and scatter:  $\langle \Delta z/(1+z) \rangle = 0.07$  and  $\sigma = 0.05$  for GOODS-N (475 galaxies) and  $\langle \Delta z/(1+z) \rangle = 0.07$  and  $\sigma = 0.06$  for GOODS-S (317 galaxies). We find that galaxies with lower probability redshifts give similar accuracy when compared to spec-zs. We therefore use all of the photometric redshifts calculated within our analysis. The fraction of catastrophic outliers is  $\sim 6$  percent for both codes. It rises to  $\sim 16$  percent for galaxies with  $|\Delta z/(1+z)| > 0.2$ . Surveys of high- $z$  galaxies using multiple medium band NIR filters find photometric redshifts similar to ours with  $\Delta z/(1+z) \sim 0.2$  (van Dokkum et al. 2009).

The relatively good agreement between photometric and spectroscopic redshifts is shown in Figure 5. The photometric redshifts of the *HYPERZ* code are plotted against the spectroscopic redshifts of GOODS-N and GOODS-S. Objects with a high probability value of  $z_{\text{phot}}$  are encircled in red. Most outliers, especially at low redshift do not have a high probability. The lower panel shows the  $\Delta z/(1+z)$  dependence on redshift  $z_{\text{spec}}$ , where there is no clear trend, or

bias, with redshift, with the possible exception of a slight trend to underestimate redshifts at high- $z$ .

We are also interested in how good our photo- $z$ s are with respect to redshift, as well as within our selection method for our sample, which uses the  $H_{160}$ -band. Thus Figure 6 shows the dependence of  $\Delta z/(1+z)$  on  $H_{160}$ -band magnitude. *HYPERZ* and *BPZ* results are plotted in red and blue, respectively. Only high probability redshift are used in this figure. The median error and rms scatter are computed in each magnitude are shown. The figure shows the slightly better performance of *HYPERZ*, which is also visible in the fraction of outliers with  $|\Delta z/(1+z)| > 0.5$ . The redshift error is stable up to faint magnitudes of  $H_{160} \sim 24$ , as is the fraction of outliers. *HYPERZ* is likely giving a superior result over *BPZ* due to the limited redshifts we can use as the Bayesian training set, which thus limits the reliability of redshifts and/or types of galaxies for which no spec- $z$ s are available. See also Conselice et al. (2007a) for a more general discussion about using different types of photo- $z$ s for galaxies with different properties.

The comparison of our results with photometric redshifts already available for the brighter part of our sample shows that our photometric redshifts are of comparable quality to those using many more photometric bands, although these necessarily are from ground-based and/or *Spitzer* imaging. Photometric redshifts taken from the FIREWORKS compilation have a median difference of  $\Delta z/(1+z) = 0.037$  and an rms scatter of  $\sigma = 0.028$  in comparison to our photometric redshifts. While we find good agreement between our photometric redshifts and previously published spectroscopic redshifts, it must be noted that most of these galaxies are fairly bright and it remains to be determined whether our agreement would be as good for much fainter galaxies.

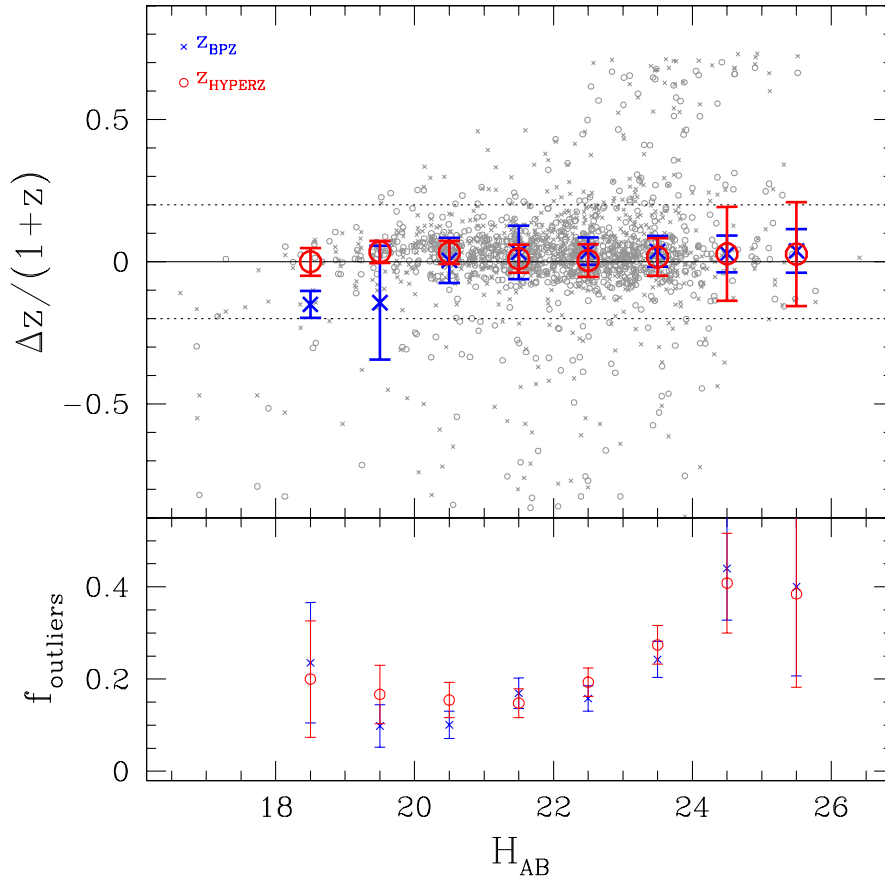
### 3.3 Stellar Masses

We calculate stellar masses for our galaxies within our global  $H_{160}$ -selected sample through the use of our optical+NIR photometry, using our own stellar mass code. The method we use to measure stellar masses involves fitting the photometric points, based on a given redshift, to simulated magnitudes based on different star formation histories, and constructing a distribution of likely stellar masses, as well as other parameters such as rest-frame optical colours, ages of the stellar population, metallicity, dust extinction, and so on. While these non-stellar mass parameters are degenerate, the stellar mass in these calculations is robust (Bundy et al. 2006).

In detail, the basic stellar mass fitting method consists of fitting a grid of model SEDs constructed from BC03 stellar population synthesis models, with different star formation histories. We use an exponentially declining model to characterise the star formation history, with various ages, metallicities, and dust contents used for different models. These models are parameterised by an age, and an e-folding time for parameterising the star formation history ( $\tau$ ), and star formation rate ( $\psi$ ) such that

$$\psi(t) \sim \psi_0 \times \exp(-t/\tau).$$

The values of  $\tau$  are uniformly selected from a range between



**Figure 6.** Dependence of  $\Delta z/(1+z)$  on  $H_{160}$  magnitude. *Top panel:*  $\Delta z/(1+z)$  vs.  $H_{160}$ -band magnitude for *HYPERZ* (red circles) and *BPZ* (blue crosses) results. Median values in each magnitude bin (width = 1 mag) are plotted as solid lines, with the rms scatter shaded in the respective color. *Bottom panel:* fraction of catastrophic outliers  $|\Delta z/(1+z)| > 0.5$  as a function of  $H_{160}$ -band magnitude. Only high probability redshifts are used in this plot.

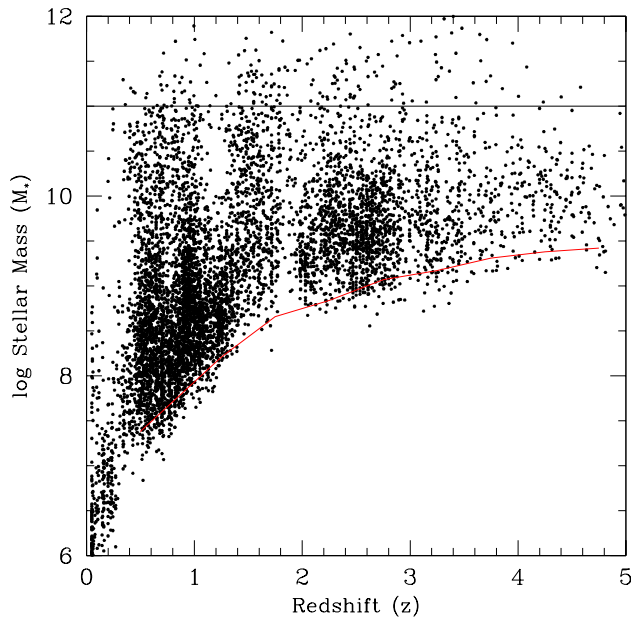
0.01 and 10 Gyr, while the age of the onset of star formation ranges from 0 to 10 Gyr. The metallicity ranges from 0.0001 to 0.05 (BC03), and the dust content is parametrised by  $\tau_v$ , the effective  $V$ -band optical depth, for which we use values  $\tau_v = 0.0, 0.5, 1$ , and 2. Although we vary several parameters, the resulting stellar masses from our fits do not depend strongly on the various selection criteria used to characterise the age and the metallicity of the stellar population (e.g., Papovich et al. 2006; Bundy et al. 2006, 2008; Conselice et al. 2007a).

It is important to realise that these parameterisations are fairly simple, and it remains possible that stellar mass from older stars is missed under brighter, younger, populations or from an incorrect star formation parametrisation. For example, Papovich et al. (2010) find that galaxies are increasing in their star formation rate at  $z > 2$ , although Papovich et al. (2010) find that this increase measured masses by a factor of 1.6 at most. Furthermore, while the majority of our systems are red galaxies it is possible that up to a factor of two in stellar mass is missed in any star-bursting blue systems. However, stellar masses measured through our technique are roughly the expected factor of five to ten times smaller than dynamical masses at  $z \sim 1$ , using a sample of disk galaxies (Conselice et al. 2005), demonstrating their in-

herent reliability to within a factor of two, similar to the estimated errors based on fitting (Bundy et al. 2006). Our method is also the same as that used to trace the evolution of massive galaxies at lower redshifts  $z < 2$  (e.g., Conselice et al. 2007; Bundy et al. 2006). Our masses also agree with results from multiple methods of measuring stellar masses for the same galaxies (Papovich et al. 2006; Yan et al. 2004; Daddi et al. 2007).

We fit the magnitudes derived from these model star formation histories to the actual data, to obtain a measurement of stellar masses using a Bayesian approach. We calculate the likely stellar mass, age, and absolute magnitudes for each galaxy at all star formation histories, and determine stellar masses based on this distribution. Distributions with larger ranges of stellar masses have larger resulting uncertainties. Typical errors for our stellar masses are 0.2 dex from the width of the probability distributions. There are also uncertainties from the choice of the IMF. Our stellar masses utilise the Salpeter IMF. There are additional random uncertainties due to photometric errors. The resulting stellar masses thus have a total random error of 0.2 – 0.3 dex, roughly a factor of two.

There is also a question as to whether or not our stellar masses are overestimated because of using the Bruzual



**Figure 7.** The distribution of redshifts and stellar masses for our  $H_{160}$ -selected GNS galaxies. The red solid line shows the evolution of the minimum stellar mass we could detect at our  $H_{160}$ -band depth as a function of redshift for a maximally old stellar population. The solid horizontal line shows the  $\log M_* > 11$  limit in which the primary sample for selection of the GNS galaxies was carried out.

& Charlot (2003) models. It has been argued by Maraston (2005), among others, that a refined treatment of thermal-pulsating asymptotic giant (TP-AGB) stars in the BC03 models results in stellar masses that can be too high by a factor of a few. While we consider an uncertainty of a factor of two in our stellar masses, it is worth investigating whether or not our sample is in the regime where the effects of a different treatment of AGB stars, as in e.g., Maraston (2005), will influence our mass measurements. This has been investigated in Maraston (2005) who have concluded that galaxy stellar masses computed with an improved treatment of AGB stars are roughly 50 – 60 percent lower.

However, the effect of TP-AGB stars is less important at the rest-frame wavelengths we probe than at longer wavelengths, especially in the rest-frame IR. Since the GNS is  $H_{160}$ -band selected, and the observed  $H_{160}$ -band is used as the flux in which stellar masses are computed, then the rest-frame wavelength probed is roughly  $\sim 0.5 \mu\text{m}$  at  $z \sim 2$ . At this wavelength, the effects of TP-AGB stars are minimised, as has been shown in previous work using the same type of data, and the same code (Conselice et al. 2007). To test this on our galaxy sample, we utilised the newer Bruzual and Charlot (2010, in prep) models, which include an improved TP-AGB star prescription. From this we find on average that stellar masses are smaller on average by  $< 0.07$  dex using the newer models. At most, the influence of TP-AGB stars will decrease our stellar masses by 20 percent. The effect of this would reduce the number of galaxies within our sample, particularly those close to the  $M_* = 10^{11} M_\odot$  boundary. This systematic error is however much smaller than both the

stellar mass error we assume (0.3 dex), and the cosmic variance uncertainties (e.g., Conselice et al. 2007), and thus we conclude that it is not a significant factor within our analysis. The stellar mass vs. redshift relation for our sample is shown in Figure 7. We analyse the stellar mass function in detail in Mortlock et al. (2010), including how photometric redshift and stellar mass uncertainties affect the stellar mass function up to  $z \sim 3.5$ , although we give an initial analysis of the number densities for massive galaxies with  $M_* > 10^{11} M_\odot$  later in this paper (§4.3.3).

## 4 ANALYSIS

### 4.1 Massive Galaxy Selection

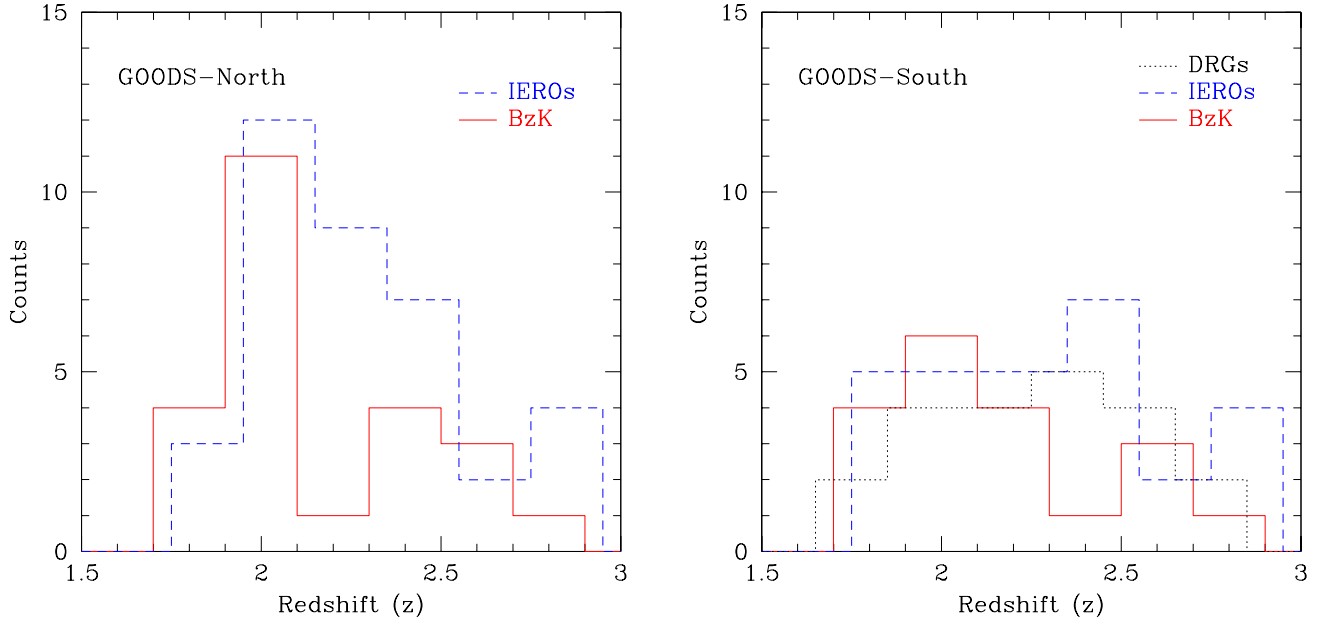
The selection of massive galaxies at high redshift is an important process which remains difficult due to the inability to easily acquire spectroscopic redshifts for a sizeable population of galaxies at  $z > 2$ . At lower redshifts ( $z < 1.4$ ), it is fairly straightforward to obtain redshifts through spectroscopic surveys such as DEEP2 or VVDS, combined with deep NIR imaging to measure stellar masses (e.g., Conselice et al. 2007; Bundy et al. 2006).

As described in our selection method for the GNS fields, there are a few approaches for determining the massive galaxy population at high redshifts. These methods typically use a colour selection of some form, ranging over wavelengths from the  $U$ -band to the infrared with *Spitzer*, which generally locate the Lyman-break through the use of deep  $U$ -band data, or the Balmer and 4000Å breaks through infrared+optical filters. However, it has never been shown that a complete sample of massive galaxies can be selected through these methods and it remains possible, or even likely, that many massive galaxies are missed by not having a colour or magnitude which fits the criteria being selected for (see §2.2). For example, ultra-dusty galaxies would possibly have spectral energy distributions that would not be included in our selection.

As discussed in §2.2, the methods for galaxy selection that we use in this paper for our primary target selection include the BzK method (Daddi et al. 2004), the IERO method (Yan et al. 2004), the DRG method (Papovich et al. 2006), and the BX/BM method (Reddy et al. 2008). In this section we give a description of the relationship between these different methods for determining the population of massive galaxies at redshifts  $z > 2$ . This has been done previously for other populations at high redshift by Reddy et al. (2005) and Grazian et al. (2007).

A graphical summary of the distribution in redshift for the colour selection methods for our massive galaxies is shown in Figure 8, and the distribution of stellar masses in Figure 9 using the initial selection described in §2.2. As can be seen in these figures, there is a slight, but insignificant, difference in the redshifts, and stellar mass selection for these massive galaxies.

We find that the BzK-selected massive galaxies tend to lie towards the lower range of redshifts, with an average in GOODS-N of  $\langle z \rangle = 2.12 \pm 0.28$  and in the GOODS-S of  $\langle z \rangle = 2.17 \pm 0.33$ . On the other hand the IEROs have a higher average redshift range, with  $\langle z \rangle = 2.24 \pm 0.28$  in the North and  $\langle z \rangle = 2.29 \pm 0.34$  in the south. The DRGs tend to



**Figure 8.** The redshift distribution of galaxies of different types. Shown in the left panel are the redshift distributions for the IEROs and BzKs denoted by dashed and solid lines, respectively, for the GOODS-N Field. The right panel shows a similar trend, except it also includes the DRG-selected galaxies. Note that if an object is selected by multiple methods, that galaxy is plotted for each type to which it belongs. It appears that the IEROs are selected from a slighter higher redshift population than the BzK galaxies.

be selected with even higher redshifts than either the BzKs and IEROs, with an average value of  $\langle z \rangle = 2.32 \pm 0.29$  in GOODS-S. However, we find that all three methods find galaxies of similar mass, with the average stellar mass for each type  $\langle M_* \rangle \sim 2 \times 10^{11} M_\odot$ , and all methods give a similar relatively large range in redshifts.

Furthermore, as can be seen by the different symbols in Figure 9, there are many massive systems which are selected by more than one method. In fact, we find that nearly all selection methods overlap with another for some galaxies. Only a small fraction of our systems are selected by just one method, with the IERO selection being the most likely method for finding unique galaxies samples.

The breakdown of our selections is such that over all galaxies in GOODS-N, 24 objects, or  $53 \pm 11$  percent of the systems are selected by the BzK method. The corresponding number is 18 systems, or  $51 \pm 12$  percent of those in the GOODS-S field. The IERO selection is the most efficient for identifying our massive galaxy sample. In the GOODS-North we find that 37 galaxies or  $82 \pm 0.14$  percent are located as IEROs, while in GOODS-S, with 27 systems the fraction is  $66 \pm 0.15$  percent. In the GOODS-S where we are able to use the DRG method, we find that a total of 21 galaxies in our massive galaxy sample are selected, or  $77 \pm 0.14$  percent. Finally, we note that only a small fraction of our sample of massive galaxies in the GOODS-North at  $1.7 < z < 2.9$  are detected through the BM/BX selection method (Reddy et al. 2008) (Figure 9).

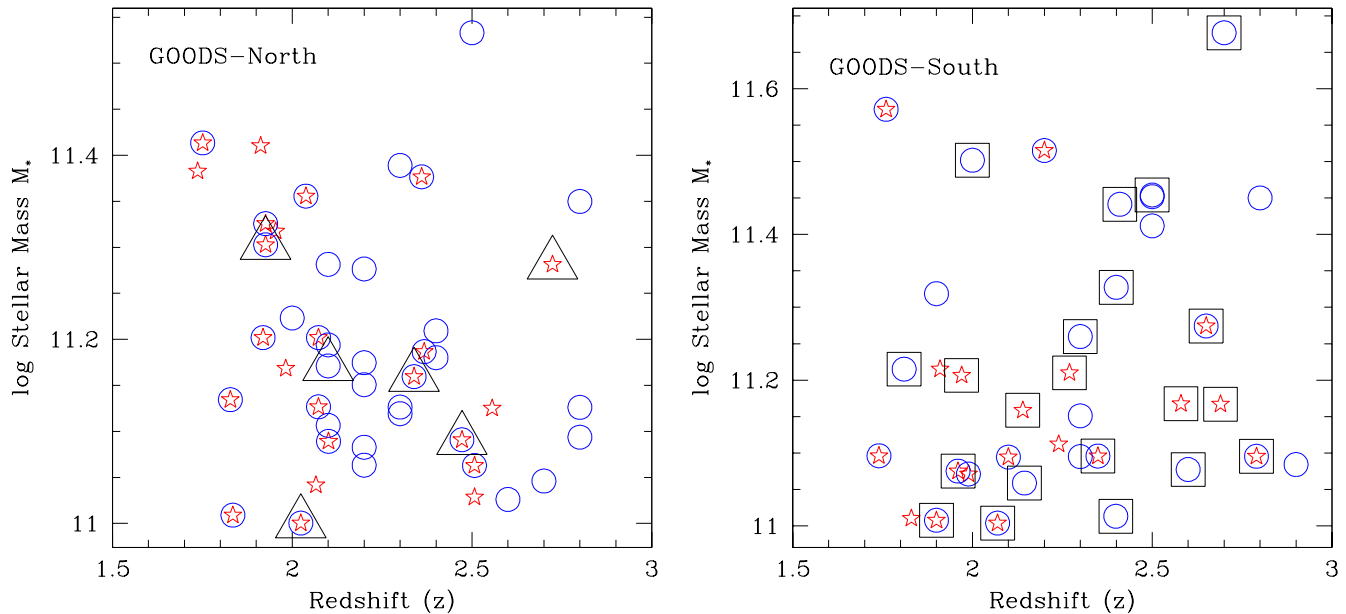
There are however a few biases which can produce some of these results. The first is that the BzK method, as described in §2.2, is limited to  $K_{\text{Vega}} = 22.0$  and  $20.5$  in the GOODS South and North, respectively. The method will

not find bluer galaxies near  $z \sim 3$ , which will drop out of the sample at around  $z \sim 2.5$ . However according to Daddi et al. (2004) (eq. 6) we will be largely complete in mass of  $M_* > 10^{11} M_\odot$  at  $z < 2.5$  – through most of our redshift range. Furthermore, the IERO selection is potentially the most successful in this experiment due to the depth of the IRAC imaging compared to the K-band data used in the DRG and BzK methods. Furthermore, the blunt colour selection for the IEROs will find more objects, although it remains possible that there are more false positives with this method of colour selection. We however conclude that no one single method for locating distant massive galaxies can be used to find complete samples and that either a combination of different methods, or a photometric redshift selected sample, is essential.

## 4.2 Stellar Mass Distribution

In this section we investigate the stellar masses which we compute based on our  $H_{160}$ –band detections matched with our ACS imaging. These stellar masses are computed as described in §3.3. This allows us to examine both the distribution of the stellar masses which we measure for the GNS sample, as well as test the differing methods outlined in §2.2 for selecting high-redshift galaxies. These stellar masses will be the focus of a detailed analysis in Mortlock et al. (2010).

We present in Figure 7 the stellar mass distribution of our sample out to  $z \sim 5$ . We also show on this figure the stellar mass of a maximally old stellar population which would still be detected at each redshift. Note that there is a slight gap near redshift  $z \sim 1.8$  which is likely partially the result of photometric redshift systematic errors. This gap is



**Figure 9.** The distribution of our initial sample of BzKs, IEROs, DRGs, and BM/BX objects from which our selection of NICMOS fields was made. The left panel shows the distribution within GOODS-N, while the right panel shows this within GOODS-S. The symbols are: stars are BzKs; open circles are IEROs; boxes are DRGs which are only found in GOODS-S; and triangles are BM/BX objects, which are only located within GOODS-N.

however also quite small roughly  $\delta z = 0.05$  in size, and there is no dependence of stellar mass or color in the galaxies that are within this gap.

We use these stellar masses to determine the completeness and ability of colour selection methods to find the highest mass galaxies at  $z > 2$ , and to measure their masses accurately. As we are using a heterogeneous selection for our high-mass sample, it is important to carry out this comparison to determine how and whether a stellar mass selected sample would be similar, and if not, then in what way it is different.

We find in our new photo- $z$ /mass  $H_{160}$ -based catalogue, independent of our original colour selection catalogue (§2.2), that between  $1.7 < z < 2.9$  there are 75 massive galaxies within our criteria of  $M_* > 10^{11} M_\odot$ , using our new  $BVizH$  stellar masses and photometric redshifts. Nearly all of these galaxies are selected by the colour methods for finding high redshift massive galaxies (§2.2), thereby showing that we have a nearly complete sample of massive galaxies at high redshift, sans systems that are extremely dusty that would not be measured with our photometric redshifts accurately. The reason there is a slight difference from our 80 original galaxies is that the computation of photometric redshifts and stellar masses from our  $H_{160}$ -band selected catalog are slightly different from those which were used to construct the original catalogue. Overall, if we consider a slightly wider stellar mass and redshift range, we are able to recover all but ten of the systems which were originally suggested by our initial colour selected analysis (§2.2) to be within our stellar mass and redshift range of interest. Although we find that some galaxies are not selected by our methods, these are likely to be systems which just missed

our initial criteria, based on our strict stellar mass and photometric redshift cut.

Overall, we find that the average stellar mass difference between our originally estimated masses, from the colour selected samples, and our new calculations, is 0.03 dex, with a larger scatter of 0.39 dex. This is slightly larger than our 0.2 dex random error measurement, and this is the result of differing redshifts between the two samples. This difference is furthermore reduced to 0.29 dex in scatter when we examine galaxies for which the two redshift estimates are within  $\delta z = 0.1$  of their pre- and post-redshift measures.

In other words, when we examine only those galaxies for which both redshift estimates are near to each other, we find a much smaller difference between the measured stellar masses. The differences in the stellar masses can be explained therefore by the fact that the redshifts are different between the two samples. We furthermore find that the photometric redshift measures for our massive galaxy sample from our original catalog compared with the new measures from the  $H_{160}$ -band selected sample are  $\delta z/(1+z) = 0.05$ , similar to the quality of our overall photo- $z$  quality when compared to the measured spectroscopic redshifts.

### 4.3 Properties of Massive Galaxies at $z > 2$

#### 4.3.1 Previous Investigations

One of the major focuses of the GNS is to examine the properties of massive galaxies at  $z > 2$ . In the past this type of analysis has generally been performed at lower redshifts, at  $z < 2$ , where properties of the massive galaxy population are now well described (e.g., Conselice et al. 2007; Trujillo et al.

2007; Bundy et al. 2008; Foucaud et al. 2010). Examining the galaxy population at higher redshifts is more challenging due to the fact that spectroscopic redshifts are difficult to obtain for a sizeable fraction of galaxies. However, some early attempts have been performed which suggest that significant information is obtainable through deep spectroscopy of distant massive galaxies (e.g., Kriek et al. 2008).

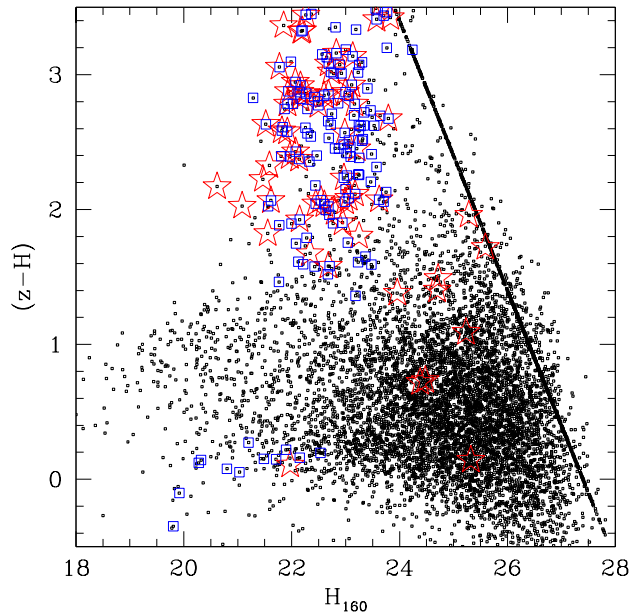
Despite the lack of spectroscopic redshifts for our sample, we can still make progress using photometric redshifts and stellar mass measures, which have already been used in many papers for understanding the evolution of the massive galaxy population at higher redshifts. While we will not providing a detailed analysis of the massive galaxy population at  $z > 2$  within this paper, we give some basic features, as well as provide information that will be used in other papers that will follow this one in terms of the analysis of these distant galaxies.

We have previously published an analysis of the size evolution of massive galaxies using this same data (e.g., Buitrago et al. 2008), finding that the sizes of our massive galaxy sample are much smaller by a factor of two to five compared with similar stellar mass selected galaxies in today's Universe. Tables 5 and 6 list the morphological properties of our original 80 galaxy sample. This include the GALFIT values of the Sersic index ( $n$ ) and the effective radii ( $R_e$ ), as well as other shape measures such as the position angle (P.A.), axis ratio ( $b/a$ ), effective surface brightness, as well as the photometric and spectroscopic redshifts for these systems.

Using this data set combined with previous work at lower redshifts (e.g., Trujillo et al. 2007; Cassata et al. 2010) that there is a gradual increase in the sizes of galaxies when viewed at lower redshifts. Understanding how these galaxies become larger at lower redshifts is one of the primary focuses of studies of massive galaxies, and a solution to this problem remains outstanding.

Another issue we have used this data set to address is the merger history of these massive galaxies at  $z < 3$  (Bluck et al. 2009, 2010 in prep). By investigating pairs of galaxies at these redshifts, we find that the merger fraction for massive galaxies contains a steep decline, which falls as  $\sim (1+z)^3$ , and that overall there are no more than roughly two or three major mergers occurring for these massive galaxies at  $z < 3$ , suggesting that at most the stellar mass is tripled by such mergers, and that furthermore, these mergers are probably not directly producing the increase in the sizes of these massive galaxies (e.g., Buitrago et al. 2008). This is further confirmed when examining similar results at lower redshifts (Conselice et al. 2009). We are currently investigating the merger history of GNS galaxies through the use of the CAS morphological parameters using the NICMOS imaging (e.g., Conselice et al. 2008; Bluck et al. 2010).

We are also investigating the star formation history for these systems by using MIPS photometry and rest-frame UV fluxes (Bauer et al. 2010; Weinzirl et al. 2010). Furthermore, we are looking at the environmental properties of our galaxies, and are comparing their environments to sim-



**Figure 10.** The  $H_{160}$ -band vs.  $(z-H)$  colour diagram for our  $H_{160}$ -band selected sample. Shown here, as red open stars, are the locations of our initial stellar mass selected sample. As can be seen, many of the massive galaxies in our sample are quite red. The apparent line on the right of the diagram is the result of galaxies which are undetected in the  $z$ -band.

ilar mass galaxies at lower redshifts (e.g., Grützbauch et al. 2010). We are also investigating the surface brightness profiles and Kormendy relations and minor merger histories for these galaxies (Bluck et al. 2010b) and at how, by comparing these measurements to simulations of nearby galaxies placed at high redshift, the evolutionary history of these galaxies can be deciphered (e.g., Conselice et al. 2010, in prep.). Finally, we are investigating the more general mass-selected population at high redshift through the evolution of stellar mass functions and colours (e.g., Mortlock et al. 2010).

#### 4.3.2 Colours

The colours of our massive galaxies are typically quite red, and most of them have colours  $(z-H) > 1.5$  (Figures 10 and 11) and with  $H_{160}$  magnitudes  $H_{160} \sim 23$  AB. In Figures 10 and 11 the original colour selected massive sample is shown by the open stars. The objects within our new photometric redshift selection which are not within the original sample also fall within this area of red colour space, as denoted by the open blue squares (Figure 10 & 11). This also shows that these galaxies are largely very faint in the optical, and that the best way to study them is in the near-infrared. However, as can be seen through the blue squares on Figure 10, some fraction of the systems which are selected by the photometric redshift technique have bluer colours, with flat spectrum colours of  $(z-H) \sim 0$ . These galaxies would not have been selected through our colour techniques due to the fact that such systems are too blue, and thus are hard to distinguish

**Table 3.** Basic information and photometry for our initial colour selected Sample of galaxies with  $M_* > 10^{11} M_\odot$  within the GOODS-North Field

| ID   | Type | RA (J2000)  | Dec (J2000) | $z_{\text{phot}}$ | $M_* (\times 10^{11} M_\odot)$ | $B_{450}$  | $V_{606}$  | $i_{775}$    | $z_{850}$  | $H_{160}$  |
|------|------|-------------|-------------|-------------------|--------------------------------|------------|------------|--------------|------------|------------|
| 43   | 4    | 189.1255493 | 62.115509   | 2.20              | 1.21                           | 27.05±0.32 | 26.82±0.20 | 26.04±0.16   | 25.44±0.10 | 22.60±0.10 |
| 77   | 1    | 189.132522  | 62.112205   | 1.91              | 2.57                           | 27.82±0.86 | 26.89±0.27 | 25.76±0.14   | 25.01±0.08 | 22.07±0.06 |
| 21   | 4    | 189.135406  | 62.117168   | 2.70              | 1.11                           | 26.16±0.07 | 25.60±0.03 | 25.35±0.03   | 25.34±0.04 | 23.96±0.16 |
| 227  | 5    | 189.119278  | 62.135971   | 2.07              | 1.59                           | 26.60±0.13 | 26.48±0.10 | 26.58±0.17   | 26.32±0.15 | 25.23±0.26 |
| 373  | 5    | 189.058517  | 62.163517   | 2.50              | 1.16                           | ...        | ...        | ...          | ...        | 22.80±0.07 |
| 552  | 5    | 189.077056  | 62.151042   | 1.92              | 2.12                           | 24.92±0.09 | 24.44±0.06 | 23.61±0.04   | 23.10±0.03 | 21.08±0.03 |
| 730  | 5    | 189.251312  | 62.152904   | 2.47              | 1.23                           | ...        | ...        | ...          | ...        | 24.35±0.15 |
| 840  | 5    | 189.173446  | 62.167392   | 1.92              | 2.01                           | 27.30±0.33 | 26.30±0.11 | 25.65±0.0908 | 25.02±0.06 | 22.15±0.06 |
| 856  | 1    | 189.178649  | 62.166355   | 1.74              | 2.41                           | 28.24±0.96 | 26.87±0.23 | 25.66±0.1146 | 24.83±0.06 | 21.77±0.05 |
| 999  | 1    | 189.142868  | 62.233570   | 1.98              | 1.47                           | 26.23±0.17 | 25.17±0.07 | 24.27±0.0463 | 23.38±0.02 | 21.56±0.06 |
| 1144 | 5    | 189.503555  | 62.270061   | 2.07              | 1.34                           | 28.80±0.65 | 28.69±0.47 | ...          | 26.99±0.18 | 22.29±0.08 |
| 1129 | 5    | 189.507492  | 62.271797   | 2.37              | 1.54                           | 29.34±0.77 | 28.28±0.23 | 27.60±0.20   | 27.65±0.23 | 23.21±0.13 |
| 1257 | 5    | 189.226257  | 62.292339   | 2.02              | 1.00                           | 29.64±2.00 | 29.03±1.03 | 26.57±0.17   | 26.27±0.14 | 23.13±0.09 |
| 1394 | 5    | 189.399597  | 62.345371   | 2.04              | 2.27                           | 27.56±0.43 | 27.57±0.37 | 26.90±0.33   | 25.71±0.12 | 22.26±0.06 |
| 1533 | 1    | 189.305038  | 62.179489   | 2.56              | 1.33                           | 25.86±0.12 | 25.57±0.08 | 25.13±0.08   | 25.10±0.09 | 24.38±0.19 |
| 1666 | 5    | 189.256576  | 62.196266   | 2.36              | 2.38                           | 27.61±0.58 | 26.90±0.27 | 25.77±0.14   | 25.30±0.10 | 21.50±0.05 |
| 1768 | 1    | 189.273559  | 62.187240   | 1.95              | 2.08                           | 28.39±0.95 | 27.31±0.28 | 26.68±0.25   | 25.53±0.09 | 22.20±0.12 |
| 1826 | 4    | 189.073135  | 62.261402   | 2.20              | 1.89                           | 25.34±0.06 | 25.21±0.05 | 25.09±0.07   | 24.64±0.05 | 22.60±0.06 |
| 1942 | 1    | 189.277557  | 62.254707   | 2.51              | 1.07                           | 25.07±0.05 | 24.61±0.03 | 24.35±0.04   | 24.07±0.03 | 22.15±0.05 |
| 2066 | 4    | 189.300201  | 62.203414   | 2.80              | 2.24                           | 26.54±0.19 | 26.83±0.19 | 25.79±0.12   | 25.66±0.12 | 23.21±0.13 |
| 2083 | 1    | 189.312072  | 62.201652   | 2.72              | 1.91                           | 27.77±0.45 | 27.65±0.30 | 26.79±0.22   | 25.99±0.11 | 22.83±0.09 |
| 2049 | 4    | 189.312988  | 62.204704   | 2.40              | 1.62                           | ...        | ...        | ...          | ...        | 23.28±0.22 |
| 2282 | 4    | 189.306976  | 62.262676   | 2.30              | 1.34                           | 28.70±0.71 | 28.12±0.34 | 27.95±0.41   | 26.98±0.18 | 23.57±0.11 |
| 2411 | 4    | 189.047927  | 62.176132   | 2.10              | 1.48                           | 27.61±0.44 | 26.44±0.13 | 26.05±0.15   | 25.54±0.10 | 22.68±0.09 |
| 2564 | 5    | 189.210907  | 62.248912   | 1.83              | 1.36                           | ...        | 27.64±0.40 | 26.46±0.22   | 25.13±0.07 | 22.26±0.07 |
| 2734 | 4    | 189.042160  | 62.146274   | 2.60              | 1.06                           | 30.15±1.85 | 28.02±0.22 | 27.76±0.31   | 27.25±0.21 | 23.83±0.13 |
| 2678 | 4    | 189.047424  | 62.148479   | 2.50              | 3.41                           | ...        | 27.23±0.29 | 26.36±0.23   | 25.50±0.11 | 22.18±0.05 |
| 2764 | 4    | 189.052475  | 62.143322   | 2.20              | 1.42                           | 26.70±0.17 | 26.21±0.09 | 25.60±0.09   | 25.20±0.07 | 22.97±0.12 |
| 2902 | 4    | 189.091293  | 62.267700   | 2.00              | 1.67                           | 28.33±0.77 | 27.16±0.22 | 26.53±0.20   | 25.95±0.13 | 23.17±0.14 |
| 2837 | 4    | 189.094375  | 62.275016   | 2.30              | 2.45                           | 25.16±0.08 | 25.02±0.06 | 24.62±0.07   | 24.26±0.05 | 22.68±0.07 |
| 2965 | 4    | 189.079818  | 62.244968   | 2.80              | 1.34                           | 29.24±2.75 | 26.26±0.13 | 25.11±0.07   | 25.14±0.08 | 23.06±0.11 |
| 3036 | 4    | 189.087020  | 62.237724   | 2.10              | 1.28                           | 25.37±0.10 | 24.93±0.06 | 24.63±0.06   | 24.01±0.04 | 22.34±0.07 |
| 3126 | 5    | 189.130340  | 62.166198   | 2.10              | 1.23                           | 27.50±0.44 | 26.44±0.13 | 26.00±0.15   | 25.29±0.09 | 23.18±0.10 |
| 3250 | 4    | 189.229095  | 62.138568   | 2.30              | 1.32                           | 26.34±0.12 | 26.44±0.09 | 26.01±0.10   | 26.04±0.11 | 23.11±0.11 |
| 3422 | 4    | 189.280883  | 62.344234   | 2.80              | 1.24                           | 28.26±0.51 | 26.82±0.14 | 26.69±0.17   | 26.47±0.15 | 23.79±0.19 |
| 3387 | 5    | 189.294021  | 62.347286   | 1.84              | 1.02                           | 28.65±1.15 | 27.52±0.29 | 26.53±0.16   | 25.75±0.09 | 22.73±0.08 |
| 3582 | 4    | 189.098754  | 62.169300   | 2.40              | 1.51                           | ...        | ...        | ...          | ...        | 23.68±0.20 |
| 3629 | 4    | 189.182952  | 62.272567   | 2.10              | 1.91                           | 26.56±0.19 | 25.44±0.05 | 24.88±0.05   | 24.40±0.04 | 21.82±0.06 |
| 3818 | 5    | 189.202041  | 62.317256   | 1.75              | 2.59                           | 28.26±1.36 | 26.47±0.25 | 25.28±0.13   | 24.15±0.05 | 21.52±0.05 |
| 3766 | 4    | 189.205612  | 62.322628   | 2.10              | 1.56                           | 26.10±2.00 | 25.44±0.08 | 24.86±0.08   | 24.51±0.06 | 22.14±0.06 |
| 3822 | 4    | 189.219863  | 62.316909   | 2.20              | 1.16                           | ...        | 29.61±1.19 | 28.48±0.62   | 27.36±0.24 | 23.46±0.09 |
| 3970 | 5    | 189.331710  | 62.205925   | 2.34              | 1.44                           | 27.66±0.43 | 27.02±0.18 | 26.15±0.13   | 25.87±0.11 | 23.00±0.10 |
| 4121 | 5    | 189.456344  | 62.233276   | 1.92              | 1.59                           | ...        | 26.29±0.08 | 25.11±0.04   | 24.70±0.03 | 21.92±0.08 |
| 4033 | 1    | 189.464111  | 62.244133   | 2.07              | 1.10                           | 24.82±0.07 | 24.54±0.06 | 23.86±0.05   | 23.68±0.05 | 21.61±0.04 |
| 4239 | 4    | 188.981262  | 62.173790   | 2.20              | 1.50                           | 26.47±0.22 | 25.97±0.11 | 25.70±0.14   | 25.05±0.09 | 22.99±0.13 |

Notes. The ID for each object is from our final NIC3 catalog of objects, the column 'Type' refers to the colour selection method in which these galaxies were found, with 1=BzK, 4=IERO, 5=BzK+IERO;  $z_{\text{phot}}$  is the initial measured photometric redshift; Mass is the stellar mass in units of  $10^{11} M_\odot$ . The remaining panels give our  $BVizH$  photometry for these systems.

from lower redshift galaxies. However, as we will see, these objects are not a dominant part of the population, and in fact most of the global quantities calculated for these massive galaxies at  $z > 2$  are largely the same whichever of these two methods for selection is used.

We can also get some basic idea of the star formation history and stellar populations of these massive galaxies by examining their position in colour-colour space (Figure 11) and their location within rest-frame colour-magnitude diagrams (Figure 12). We only show galaxies down to  $M_* = 10^{10} M_\odot$  on these colour-magnitude diagrams, where we are complete in our selection of galaxies. What we find is that our massive galaxies span a range in  $(B - z)$  colour, but are all fairly red in  $(z - H)$ , with values larger than  $(z - H) = 2$  for most systems. We find that a large fraction of our massive galaxy systems are within the star-forming region of the BzK diagnostic plots (e.g., Daddi et al. 2007; Lane et al. 2007), after converting the diagnostics to a BzH selection using a typical colour of  $(H - K) \sim 0.25$  for a galaxy at  $z \sim 2$ . This implies that within this selection, there are a significant number of galaxies with enough observed  $B$ -band flux to be considered star-forming systems (see also Bauer et al. 2010). The lines on Figure 11 furthermore show where various single stellar populations would lie in this parameter space whose colours are affect simply by  $k$ -corrections.

We furthermore use the redshifts and magnitudes of our galaxies to calculate rest-frame  $(U - B)$  colours, which are

directly compared with colours from lower redshift galaxies of similar masses (e.g, Conselice et al. 2007). The result of this rest-frame  $U - B$  vs.  $M_B$  diagram is shown in Figure 12, where we have divided up our sample into ultra-massive galaxies with  $M_* > 10^{11.5} M_\odot$ , medium mass galaxies with  $10^{11.5} M_\odot > M_* > 10^{11} M_\odot$  and those systems with more modest, but still relatively high masses, with  $10^{11} M_\odot > M_* > 10^{10} M_\odot$ . We also show this evolution in colour-magnitude for our galaxies divided into different redshift bins. Note that we are complete for  $M_* > 10^{11} M_\odot$  galaxies up to  $z = 3$ . The blue and red lines on Figure 12 show the demarcation between the red sequence and the blue cloud, and the location of the red sequence as seen at lower redshifts (Faber et al. 2007). These lines are evolved passively from lower redshift to higher- $z$ .

What one can see immediately from Figure 12 is that most of the massive galaxies, which tend also to be bright, are near or close to the red-sequence, while the lower mass galaxies are more often bluer systems, with in fact, very few of the galaxies with lower masses in our sample within the red sequence. The bi-modality is particularly present at  $2.5 < z < 3$ , where nearly all the massive galaxies with  $M_* > 10^{11} M_\odot$  are exclusively on the red sequence, while those less massive galaxies are found within the blue cloud. As we go to lower redshift it appears that some of the massive galaxies are now seen in the blue cloud.

This apparent evolution from the red sequence to the

**Table 4.** Basic information and photometry for our initial colour selected sample of galaxies with  $M_* > 10^{11} M_\odot$  within the GOODS-South Field

| ID   | Type | RA (J2000) | Dec (J2000) | $z_{\text{phot}}$ | Mass ( $\times 10^{11} M_\odot$ ) | $B_{450}$        | $V_{606}$        | $i_{775}$        | $z_{850}$        | $H_{160}$        |
|------|------|------------|-------------|-------------------|-----------------------------------|------------------|------------------|------------------|------------------|------------------|
| 4299 | 6    | 53.0918007 | -27.8028107 | 2.40              | 2.13                              | 27.01 $\pm$ 0.19 | 25.78 $\pm$ 0.06 | 25.65 $\pm$ 0.08 | 25.47 $\pm$ 0.08 | 25.32 $\pm$ 0.22 |
| 4281 | 6    | 53.0938988 | -27.8011951 | 2.60              | 1.20                              | 25.63 $\pm$ 0.05 | 25.49 $\pm$ 0.04 | 25.40 $\pm$ 0.07 | 25.21 $\pm$ 0.06 | 24.48 $\pm$ 0.14 |
| 4348 | 3    | 53.1008377 | -27.8082333 | 1.97              | 1.61                              | ...              | 29.03 $\pm$ 0.62 | 27.20 $\pm$ 0.20 | 27.24 $\pm$ 0.23 | 25.28 $\pm$ 0.28 |
| 4434 | 6    | 53.0976601 | -27.7153015 | 2.14              | 1.15                              | 25.80 $\pm$ 0.07 | 25.18 $\pm$ 0.04 | 24.80 $\pm$ 0.04 | 24.49 $\pm$ 0.03 | 22.44 $\pm$ 0.05 |
| 4399 | 4    | 53.1008263 | -27.7117653 | 2.30              | 1.25                              | 26.96 $\pm$ 0.18 | 26.47 $\pm$ 0.10 | 26.24 $\pm$ 0.14 | 26.20 $\pm$ 0.15 | 24.71 $\pm$ 0.23 |
| 4557 | 3    | 53.0891876 | -27.7600765 | 2.27              | 1.62                              | 27.40 $\pm$ 0.51 | 26.88 $\pm$ 0.29 | 25.93 $\pm$ 0.20 | 24.82 $\pm$ 0.08 | 21.94 $\pm$ 0.08 |
| 4754 | 6    | 53.1201096 | -27.8082657 | 2.00              | 3.18                              | 29.09 $\pm$ 1.06 | 28.38 $\pm$ 0.51 | 27.14 $\pm$ 0.28 | 26.30 $\pm$ 0.14 | 22.73 $\pm$ 0.08 |
| 4706 | 7    | 53.1231232 | -27.8033943 | 2.34              | 1.25                              | 28.06 $\pm$ 0.54 | 26.44 $\pm$ 0.09 | 25.63 $\pm$ 0.07 | 24.99 $\pm$ 0.04 | 22.16 $\pm$ 0.08 |
| 4882 | 5    | 53.1717033 | -27.8256683 | 1.74              | 1.25                              | 27.61 $\pm$ 0.40 | 26.34 $\pm$ 0.11 | 25.14 $\pm$ 0.06 | 24.36 $\pm$ 0.04 | 21.97 $\pm$ 0.05 |
| 4941 | 1    | 53.2300110 | -27.8507748 | 1.83              | 1.02                              | 26.87 $\pm$ 0.17 | 26.38 $\pm$ 0.10 | 26.14 $\pm$ 0.13 | 26.34 $\pm$ 0.17 | 21.60 $\pm$ 0.05 |
| 5171 | 6    | 53.0632668 | -27.6996498 | 2.39              | 1.03                              | 26.39 $\pm$ 0.12 | 25.56 $\pm$ 0.05 | 25.04 $\pm$ 0.05 | 24.84 $\pm$ 0.05 | 22.94 $\pm$ 0.08 |
| 5281 | 5    | 53.0859909 | -27.7091026 | 2.10              | 1.24                              | ...              | 28.37 $\pm$ 0.35 | 27.33 $\pm$ 0.22 | 27.31 $\pm$ 0.25 | 25.59 $\pm$ 0.26 |
| 5445 | 6    | 53.1245880 | -27.8932495 | 2.50              | 2.85                              | ...              | ...              | ...              | ...              | 23.54 $\pm$ 0.12 |
| 5372 | 4    | 53.1255684 | -27.8864536 | 2.90              | 1.21                              | 27.35 $\pm$ 0.24 | 26.14 $\pm$ 0.08 | 25.77 $\pm$ 0.10 | 25.69 $\pm$ 0.10 | 23.62 $\pm$ 0.15 |
| 5533 | 7    | 53.1289139 | -27.9036846 | 2.79              | 1.25                              | ...              | ...              | ...              | ...              | 23.60 $\pm$ 0.11 |
| 5524 | 3    | 53.1332588 | -27.9029388 | 2.58              | 1.47                              | ...              | 26.22 $\pm$ 0.06 | 25.20 $\pm$ 0.04 | 25.09 $\pm$ 0.04 | 22.17 $\pm$ 0.07 |
| 5764 | 7    | 53.2252083 | -27.8738060 | 2.65              | 1.88                              | ...              | 28.23 $\pm$ 0.46 | 27.21 $\pm$ 0.29 | 26.50 $\pm$ 0.17 | 22.66 $\pm$ 0.07 |
| 5853 | 6    | 53.0508537 | -27.7137222 | 2.41              | 2.76                              | 26.35 $\pm$ 0.20 | 25.70 $\pm$ 0.09 | 25.61 $\pm$ 0.15 | 25.05 $\pm$ 0.11 | 23.25 $\pm$ 0.15 |
| 5933 | 6    | 53.0542488 | -27.7216587 | 2.30              | 1.82                              | ...              | 28.94 $\pm$ 0.47 | 28.00 $\pm$ 0.33 | 27.54 $\pm$ 0.26 | 23.32 $\pm$ 0.11 |
| 6035 | 4    | 53.0555954 | -27.8740025 | 1.90              | 2.08                              | 27.52 $\pm$ 0.00 | 26.98 $\pm$ 0.23 | 25.73 $\pm$ 0.13 | 25.21 $\pm$ 0.10 | 21.85 $\pm$ 0.06 |
| 6114 | 1    | 53.0656776 | -27.8788643 | 2.24              | 1.30                              | 28.19 $\pm$ 0.66 | 26.20 $\pm$ 0.10 | 25.57 $\pm$ 0.09 | 24.50 $\pm$ 0.04 | 21.92 $\pm$ 0.05 |
| 6220 | 7    | 53.0717087 | -27.8436356 | 1.90              | 1.02                              | 27.19 $\pm$ 0.37 | 26.79 $\pm$ 0.19 | 25.91 $\pm$ 0.14 | 25.27 $\pm$ 0.09 | 22.50 $\pm$ 0.07 |
| 6352 | 7    | 53.0773201 | -27.8595829 | 1.96              | 1.19                              | ...              | 28.90 $\pm$ 0.62 | 28.65 $\pm$ 0.83 | 27.00 $\pm$ 0.21 | 22.37 $\pm$ 0.08 |
| 6468 | 4    | 53.1385193 | -27.6717854 | 2.80              | 2.82                              | 25.92 $\pm$ 0.18 | 26.12 $\pm$ 0.16 | 25.25 $\pm$ 0.12 | 24.78 $\pm$ 0.08 | 22.80 $\pm$ 0.10 |
| 6584 | 5    | 53.0260849 | -27.6909122 | 1.99              | 1.18                              | 26.54 $\pm$ 0.0  | 27.42 $\pm$ 0.56 | 25.95 $\pm$ 0.25 | 24.50 $\pm$ 0.09 | 22.07 $\pm$ 0.09 |
| 6575 | 4    | 53.0354462 | -27.6900806 | 2.50              | 2.58                              | 25.03 $\pm$ 0.07 | 26.12 $\pm$ 0.16 | 25.53 $\pm$ 0.16 | 24.61 $\pm$ 0.08 | 22.54 $\pm$ 0.12 |
| 6876 | 4    | 53.0400429 | -27.6852055 | 2.50              | 2.83                              | 26.30 $\pm$ 0.00 | 27.08 $\pm$ 0.27 | 25.98 $\pm$ 0.17 | 25.55 $\pm$ 0.15 | 22.98 $\pm$ 0.16 |
| 7090 | 6    | 53.0578766 | -27.8335018 | 2.70              | 4.75                              | ...              | ...              | ...              | ...              | 22.22 $\pm$ 0.06 |
| 7155 | 3    | 53.1175194 | -27.9107571 | 2.69              | 1.47                              | 28.32 $\pm$ 0.73 | 26.84 $\pm$ 0.17 | 26.09 $\pm$ 0.14 | 26.10 $\pm$ 0.16 | 24.70 $\pm$ 0.39 |
| 7320 | 7    | 53.1156578 | -27.8717003 | 2.07              | 1.01                              | ...              | ...              | ...              | ...              | 26.36 $\pm$ 0.53 |
| 7425 | 6    | 53.1271477 | -27.8345642 | 1.81              | 1.64                              | 27.46 $\pm$ 0.36 | 26.21 $\pm$ 0.15 | 24.91 $\pm$ 0.08 | 23.91 $\pm$ 0.03 | 21.59 $\pm$ 0.06 |
| 7677 | 5    | 53.1830482 | -27.7089996 | 1.76              | 3.73                              | 26.32 $\pm$ 0.26 | 25.55 $\pm$ 0.11 | 23.80 $\pm$ 0.04 | 22.79 $\pm$ 0.02 | 20.62 $\pm$ 0.04 |
| 7970 | 4    | 53.0282135 | -27.7788277 | 2.30              | 1.41                              | 27.80 $\pm$ 0.52 | 27.56 $\pm$ 0.38 | 26.22 $\pm$ 0.18 | 25.77 $\pm$ 0.14 | 22.69 $\pm$ 0.06 |
| 8140 | 1    | 53.1410255 | -27.7667332 | 1.91              | 1.64                              | 25.76 $\pm$ 0.10 | 25.10 $\pm$ 0.06 | 24.45 $\pm$ 0.05 | 23.69 $\pm$ 0.03 | 21.47 $\pm$ 0.05 |
| 8213 | 3    | 53.1628799 | -27.7122879 | 2.14              | 1.44                              | 23.05 $\pm$ 0.02 | 22.83 $\pm$ 0.01 | 22.30 $\pm$ 0.01 | 22.07 $\pm$ 0.01 | 21.97 $\pm$ 0.06 |

Notes. The ID for each object is from our final NIC3 catalog of objects, the column 'Type' refers to the colour selection method in which these galaxies were found, with 1=BzK, 3=BzK+DRG, 4=IERO, 5=BzK+IERO, 6=DRG+IERO, 7=BzK+DRG+IERO;  $z_{\text{phot}}$  is the initial measured photometric redshift; Mass is the stellar mass in units of  $10^{11} M_\odot$ . The remaining panels give our *BVizH* photometry for these systems.

blue cloud is likely due to the fact that the number densities of massive galaxies increases with time, and thus massive galaxies at  $1.5 < z < 2.0$  are not the same type of system found at higher redshifts. In other words, the build-up of massive galaxies occurs by adding bluer galaxies, that were formerly lower mass earlier, to the high mass bin. Furthermore, as discussed in Bauer et al. (2010), the fact that these massive galaxies are red does not necessarily imply that they are 'red and dead', but in fact, that they are undergoing dusty star formation (e.g., Papovich et al. 2006). A detailed discussion of this is presented in Bauer et al. (2010) and Grützbauch et al. (2010).

#### 4.3.3 The Evolution of Massive Galaxy Number Densities

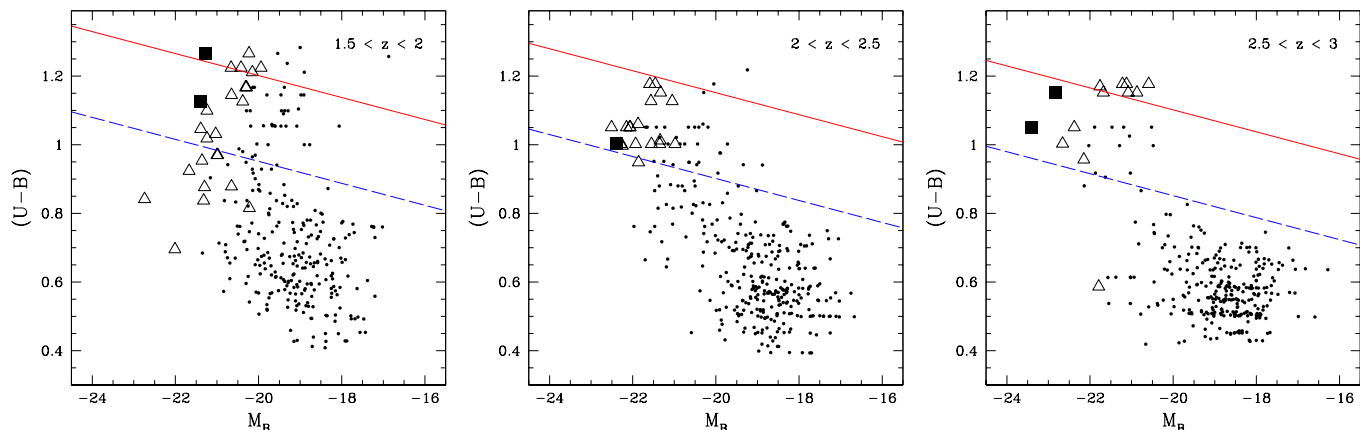
One of the major ways to examine the evolution of massive galaxies is to investigate how their number densities evolve with time (e.g., Conselice et al. 2007). Various studies have previously examined how luminosity and mass-selected samples have evolved over redshift. A very popular way to do this is by examining galaxy luminosity functions, typically in the *B*-band, and to fit the distribution of luminosities to a Schechter function, giving a characteristic luminosity  $L^*$  as well as a faint-end slope ( $\alpha$ ), and normalization given by the parameter  $\phi$ . Typically one measures evolution in the galaxy population by fitting these parameters, and then determining how they have evolved over time. This is useful for determining how the global galaxy population changes, or in the case of faint or low mass galaxies, through examining how the  $\alpha$  parameter evolves with redshift.

An alternative approach is to examine galaxies based on a certain luminosity or stellar mass threshold, such as our

selection in this paper of  $M_* > 10^{11} M_\odot$ . There are many reasons for believing that stellar mass is a better indicator for tracing the evolution of galaxies than luminosity. One reason is that stellar mass measurements in principle do not depend upon the ongoing star formation rate, whereby for a higher star formation rate the galaxy will appear brighter, but whose star formation can be revealed through its SED, and which can be normalised out.

We have also found within the GNS, and at  $z < 1$  within the *POWIR* survey (Conselice et al. 2008), that stellar mass is the most important quantity for determining the properties of a galaxy, such as its colour and star formation rate (e.g., Grützbauch et al. 2010a,b). There is a strong correlation up to  $z \sim 3$ , such that we find that galaxies are redder at high stellar masses than bluer galaxies at lower masses. This trend stays the same at all redshifts thus far probed, and a similar trend can be seen when considering the star formation rate and the specific star formation rate correlations with stellar mass.

Previously, the number densities of  $M_* > 10^{11} M_\odot$  galaxies at  $z < 2$  were investigated using the *POWIR/DEEP2* data set (Conselice et al. 2007). It was found in this previous paper that the number densities of these massive galaxies, and more specifically, those of masses  $10^{11.5} M_\odot$ , were largely in place at  $z = 1 - 1.5$ , and with a significant number of systems present at  $z = 2$ . The fact that these massive galaxies already exist in large numbers at this redshifts, suggests that we have to go to higher redshifts to trace the evolution of these systems. This was one reason for carrying out the GNS survey, for which we can make an estimate of the number densities of massive galaxies at even higher redshifts.



**Figure 12.** Colour-magnitude diagram in rest-frame units for our sample of galaxies. Shown are the data plotted in different ways depending on their stellar mass. The most massive galaxies with  $M_* > 10^{11.5} M_\odot$  are shown as solid squares, those at  $10^{11} M_\odot < M_* < 10^{11.5} M_\odot$  are shown as open triangles, and the dots are for those galaxies with stellar masses,  $M_* < 10^{11} M_\odot$ . The red solid line is the red sequence as determined by Faber et al. (2007), while the blue dashed line shows the separation at which galaxies are considered to be within the blue cloud. Both of these lines are evolved with redshifts for a passively evolving stellar population.

We do this in two ways – both by using our original colour-selected, and likely slightly inhomogeneous sample, as well as by the use of our newly measured photometric redshifts and stellar masses from our *BVizH* selected sample (Figure 13). The errors on this plot result from number counting statistics only.

In Figure 13 we have down-weighted the stellar mass densities at  $1.7 < z < 2.9$  to account for the fact that our fields were selected to contain massive galaxies with  $M_* > 10^{11} M_\odot$ . The GNS fields were selected based on having at least one colour selected massive galaxies at  $1.7 < z < 2.9$  in the NIC3 field of view within the GOODS South and North. These fields were however not over selected for massive galaxies, as the number of other objects (drop-outs, sub-mm galaxies, BM/BX galaxies) were used to make the final selection, as well as lower mass BzKs, DRGs, and IEROs.

Ultimately the selection used 80 unique  $M_* > 10^{11} M_\odot$  galaxies. We calculate the correction factor for this selection by using the original list of massive galaxies with these redshifts and stellar masses from the colour-selected lists over the entire GOODS fields, and calculate how many non-overlapping massive galaxies there are. We find 92 of these systems in the North and 83 in the South. This gives a surface density of  $0.58 \text{ arcmin}^{-2}$ . The 80 galaxies within the GNS area provides a surface density of  $1.77 \text{ arcmin}^{-2}$  in the NICMOS pointings. Thus, the ratio of these gives the over-density for  $M_* > 10^{11} M_\odot$  galaxies at  $z > 1.7$  and  $z < 2.9$  in the NICMOS data, which is a factor of 3.05 which we use to down-weight the number densities we calculate for the  $M_* > 10^{11} M_\odot$  galaxies.

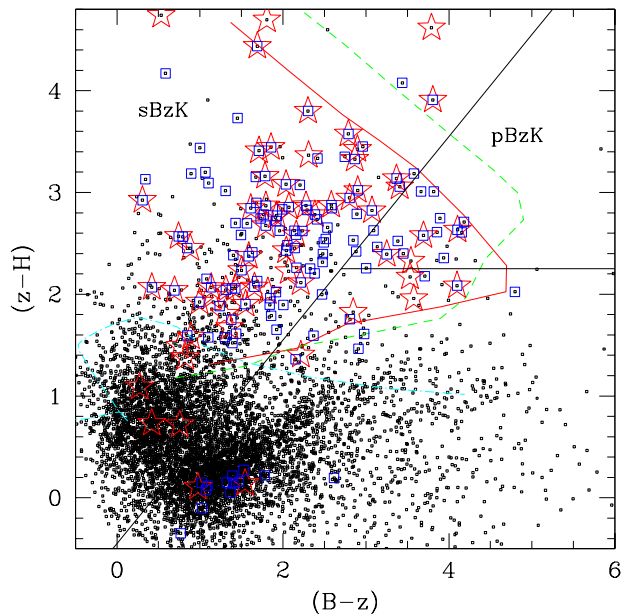
Using this, what we find is that the massive galaxy density is roughly constant and similar to its value at  $z \sim 0$  up

to  $z = 1.5$ , with a decline thereafter. There is then a real decline at higher redshifts, such that the number density for these massive galaxies grows by a factor of eight between  $z = 3$  and  $z = 1.5$ . We find this is the case for both selection methods for these massive galaxies. This demonstrates that this epoch between  $z = 1.5 - 3$  is when a large fraction of massive galaxies become massive, and thus physical processes are ongoing during this epoch which produces this increase of almost a factor of ten in the number of massive galaxies with  $M_* > 10^{11} M_\odot$  during this relatively short period of  $\sim 2$  Gyr. Future GNS papers will address the physical mechanisms which are producing this evolution.

## 5 SUMMARY

The GOODS NICMOS Survey (GNS) is a 180 orbit *Hubble* Space Telescope programme designed to obtain deep NICMOS  $H_{160}$ -band imaging of over 80 massive  $> 10^{11} M_\odot$  galaxies at  $1.7 < z < 2.9$ . The depths reached are  $H_{160} \sim 26.8 \text{ AB}$  ( $5 \sigma$ ), allowing for a range of other science questions to be addressed, including examining the lower mass galaxy population present within the same fields and redshifts. In this paper we describe the GNS survey, give information about its field selection, as well as a description of the types of galaxies we initially select for field placement, and how this compares to a newer *BVizH* photo- $z$  selection based on the combination of  $H_{160}$ -band and ACS data. We utilize only these five filters so as to have a high fidelity in our photometry quality, depth, and resolution. Our photo- $z$ s are in fact very good, with a typical  $\delta z / (1 + z) \sim 0.1$ .

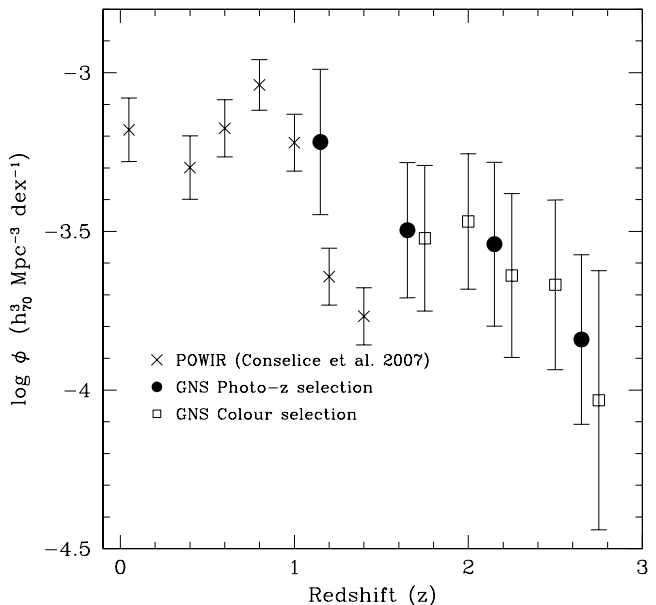
We also examine in this paper ways to select massive



**Figure 11.** The  $(z-H)$  vs.  $(B-z)$  diagram for the  $H_{160}$ -band selected galaxies in our sample. The red stars show the location of our initial massive galaxy sample based on colour selections (§2.2), while the blue squares show the location of massive systems with  $M_* > 10^{11} M_\odot$  at  $1.8 < z < 3.0$  identified through photometric redshifts. The various lines on this figure show the change in colour for simple single stellar populations of a given age as observed at various redshifts. Changes in colour seen for these models are purely due to redshift effects. The cyan dot-dashed line shows the evolution of a 100 Myr single stellar population from redshifts of  $z = 0$  to  $z = 3.8$ . The green dashed line shows a 2.5 Gyr single stellar population as observed at redshifts from  $z = 0$  to  $z = 2.6$ , while the red solid line shows a 11 Gyr old stellar population as viewed from  $z = 0$  to  $z = 2.2$ .

galaxies at high redshift  $z > 2$  in the absence of a significant number of spectroscopic redshifts. A very popular method for determining a galaxy population at  $z > 2$  is through the use of various colour cuts, e.g., BzK galaxies, DRGs, or Lyman-break galaxies. We find overall that no one single colour criterion is able to account for all massive galaxies, and that there is considerable overlap between the various methods, many of which find the same galaxies. Overall, we find that the BzK, DRG and IERO overlap, with over 50 percent between any two types. IEROs are the type which most overlaps the other two, and perhaps provides the most complete sample of at least the red galaxies selected at higher redshifts.

We show that a photometric redshift selection with a strict narrow redshift and stellar mass range gives slightly different galaxy populations than the cumulative colour selection. In particular we find that there are more blue massive galaxies at  $z > 2$  than what is found through the standard colour cuts. Galaxies absent from each of these bins are missed as they are just outside the stringent mass and redshift selection criteria we have imposed. A similar issue is present for the colour-selection of high- $z$  galaxies – there is always a population just outside a colour-selection that has intrinsic properties nearly identical to the galaxies within the



**Figure 13.** The number density evolution in units of  $h_{70}^3 \text{ Mpc}^{-3}$  for galaxies with stellar masses,  $M_* > 10^{11} M_\odot$  as seen within the GNS and within the *POWIR* survey (Conselice et al. 2007a). We show here the number densities calculated using two different galaxy sample selections, both a photo- $z$  method and the original colour-selection method, with both methods showing relatively good agreement.

original colour based selection. This is especially the case if one considers galaxies selected by stellar mass and redshift. We find, however, that this is not a significant limitation, as we obtain the same number densities and average properties using a colour selection and a photo- $z$  selection.

We also provide a summary of our understanding of how these massive galaxies evolve at high redshifts and how they are connected to lower redshift massive galaxies. Our conclusions regarding an analysis of the massive galaxy population reveal that major mergers are not adequate for driving the evolution of massive galaxies at  $z < 3$  (Bluck et al. 2009). Our conclusions based on an examination of the major merger rate at  $z \sim 2-3$  (Bluck et al. 2009), and the star formation properties (Weinzirl et al. 2010, in prep) of the massive galaxies, suggests that other mechanisms, such as minor mergers and/or gas accretion and subsequent star formation are also needed to produce the increase in stellar mass within these galaxies over time. Furthermore, the ‘disky’ nature of a large fraction of the massive galaxies at  $z \sim 2-3$ , and their star formation properties (Weinzirl et al. 2010) raises questions on the importance of major mergers in building such systems up at  $z > 3$ .

We find that even at  $z \sim 2.5$  there is a broad colour-magnitude bimodality in galaxies, such that the massive systems are nearly always red and luminous, while lower mass galaxies tend to be much bluer. The build up of the red sequence at  $z > 2.5$  is further investigated in Grützbaach et al. (2010).

We are also investigating various other properties of these massive galaxies, including the AGN content and how

AGN in massive galaxies evolves through time (Bluck et al. 2010; Weinzierl et al. 2010), including how much energy the AGN inputs into the galaxy while it is evolving. Details of these calculations will be presented in future GNS papers utilising the data from this paper, as well as data from other space and ground based telescopes, such as *Spitzer* and *Chandra*.

In the future, to make progress with massive galaxy evolution in the redshift range  $z > 2$  will require either a very large number of reliable photometric redshifts, that are studied in a statistical sense, or ultimately through spectroscopic surveys that will acquire redshifts and other physical information for distant massive galaxies. This should be possible with multi-object NIR spectroscopy which is now becoming feasible with new instrumentation on 8-10m class telescopes. Probing massive galaxy formation at higher redshifts will require even larger telescopes and instruments and will likely be a major focus of JWST and the TMT/ELT/GMT era.

The data and catalogs as used in the GNS survey are online at: <http://www.nottingham.ac.uk/astronomy/gns/>. We thank Will Hartley for providing diagnostic lines of stellar populations, as well as Omar Almaini for discussions on various aspects of this analysis. We thank STFC for support through studentships and PDRA funding. Support was also provided by NASA/STScI grant HST-GO11082. S. J. and T. W. acknowledges support from the National Aeronautics and Space Administration (NASA) LTSA grant NAG5-13063, NSF grant AST-0607748, and *HST* grant GO-11082 from STScI, which is operated by AURA, Inc., for NASA, under NAS5-26555.

## REFERENCES

- Balestra, I. et al. 2010, *A&A*, 512, 12  
 Barger, A. et al., 2008, *ApJ* 689, 687  
 Beckwith, S., et al. 2006, *AJ*, 132, 1729  
 Benitez, N. 2000, *ApJ* 536, 571  
 Benitez, N. 2000, *ApJ*, 536, 571  
 Bertone, S., Conselice, C.J. 2009, *MNRAS*, 396, 2345  
 Bluck, A.F.L., Conselice, C.J., Bouwens, R.J., Daddi, E., Dickinson, M., Papovich, C., Yan, H. 2009, *MNRAS*, 394, 51L  
 Bluck, A.F.L., Conselice, C.J., Almaini, O., Laird, E.S., Nandra, K., Gruetzbauch, R. *MNRAS* in press, arXiv:1008.2162  
 Bohlin, R.C., Mack, J., Hartig, G., Sirianni, M. 2005, Instrument Science Report ACS, 2005-12  
 Bolzonella, M. et al. 2000, *A&A* 363, 476  
 Bouwens, R.J., Illingworth, G.D., Franx, M., Ford, H. 2007, *ApJ*, 670, 928  
 Bouwens, R.J., et al. 2010, arXiv:1003.1706  
 Bouwens, R.J., et al. 2009, *ApJ*, 705, 936  
 Bruzual, G., Charlot, S. 2003, *MNRAS*, 344, 1000  
 Buitrago, F., Trujillo, I., Conselice, C.J., Bouwens, R.J., Dickinson, M., Yan, H. 2008, *ApJ*, 687, 61L  
 Bundy, K., et al. 2006, *ApJ*, 651, 120  
 Bundy, K., et al. 2008, *ApJ*, 681, 931  
 Calzetti et al. 2000, *ApJ* 533, 682  
 Casey, C.M., Chapman, S.C., Muxlow, T.W.B., Beswick, R.J., Alexander, D.M., Conselice, C.J. 2009, *MNRAS*, 395, 1249  
 Cassata, P., et al. 2010, *ApJ*, 714, 79  
 Conselice, C.J., Bershad, M.A., Dickinson, M., Papovich, C. 2003, *AJ*, 126, 1183  
 Conselice, C.J. Bundy, K., Ellis, R.S., Brichmann, J., Vogt, N.P., Philips, A.C. 2005, *ApJ*, 628, 160  
 Conselice, C.J., et al. 2007a, *MNRAS*, 381, 962  
 Conselice, C.J., et al. 2007b, *ApJ*, 660, 55L  
 Conselice, C.J., Rajgor, S., Myers, R. 2008, *MNRAS*, 386, 909  
 Conselice, C.J., Bundy, K., U, V., Eisenhardt, P., Lotz, J., Newman, J. 2008, *MNRAS*, 383, 1366  
 Conselice, C.J., Yang, C., Bluck, A., 2009, *MNRAS*, 394, 1956  
 Daddi, E., et al. 2004, *ApJ*, 617, 746  
 Daddi, E., et al. 2007, *ApJ*, 670, 156  
 Davis, M., et al. 2007, *ApJ*, 660, 1L  
 de Jong, R.S. et al. 2006, Instrument Science Report NICMOS 2006-003  
 Dickinson, M., et al. 2000, *ApJ*, 531, 624  
 Dickinson, M., et al. 2004, 600, 99L  
 Faber, S.M., et al. 2007, *ApJ*, 665, 265  
 Finkelstein, S.L., Papovich, C., Giavalisco, M., Reddy, N.A., Ferguson, H.C., Koekemoer, A.M., Dickinson, M. 2010, *ApJ*, 719, 1250  
 Foucaud, S., Conselice, C.J., Hartley, W.G., Lane, K.P., Bamford, S.P., Almaini, O., Bundy, K. 2010, *MNRAS*, 406, 147  
 Franx, M., et al. 2003, *ApJ*, 587L, 79  
 Giavalisco, M., et al. 2004, *ApJ*, 600, 93L  
 Grazian, A. et al. 2007, *A&A*, 465, 393  
 Greve, T.R., Pope, A., Scott, D., Ivison, R.J., Borys, C., Conselice, C.J., Bertoldi, F. 2008, *MNRAS*, 389, 1489  
 Guhathakurta, P., Tyson, J.A., Majewski, S.R. 1990, *ApJ*, 357, 9L  
 Jogee, S., et al. 2009, *ApJ*, 697, 1971  
 Kajisawa, M. et al. 2009, *ApJ*, 702, 1393  
 Kriek, M. et al. 2008, *ApJ*, 677, 218  
 Lane, K., et al. 2007, *MNRAS*, 379, 25L  
 Le Fevre, O., et al. 2005, *A&A*, 439, 845  
 Lotz, J.M., et al. 2008, *ApJ*, 672, 177  
 Luo, G. et al. 2008, *ApJS*, 179, 19  
 Magee, D., Bouwens, R., Illingworth, G. 2007, *ASPC*, 376, 261  
 Maraston, C. 2005, *MNRAS*, 362, 799  
 Metcalfe, N. Shanks, T., Weilbacher, P.M., McCracken, H.J., Fong, R., Thompson, D. 2006, *MNRAS*, 370, 1257  
 Papovich, C., et al. 2006, *ApJ*, 640, 92  
 Papovich, C., Finkelstein, S.L., Ferguson, H.C., Lotz, J.M., Giavalisco, M. 2010, arXiv:1007.4554  
 Popesso, P. et al. 2009, *A&A*, 494, 443  
 Ravindranath, S., et al. 2006, *ApJ*, 652, 963  
 Reddy, N., et al. 2005, *ApJ*, 633, 748  
 Reddy, N., Steidel, C.C., Pettini, M., Adelberger, K.L., Shapely, A.E., Erb, D.K., Dickinson, M. 2008, *ApJS*, 175, 48  
 Retzlaff, J. et al. 2010, *A&A*, 511, 50

**Table 5.** Structural parameters for galaxies with  $M_* > 10^{11} M_\odot$  within the GOODS-N field.

| ID   | $R_e^a$ (arcsec) | Sersic $n^a$ | b/a  | P.A. (deg) | $\mu_{\text{eff}}$ (mag arcsec $^{-2}$ ) | $z_{\text{spec}}$ | sep (arcsec) | $z_{\text{phot}}$ |
|------|------------------|--------------|------|------------|--|-------------------|--------------|-------------------|
| 43   | 0.14±0.00        | 1.67±0.05    | 0.75 | 50.6       | 17.26                                    | ...               | ...          | 1.56              |
| 77   | 0.35±0.01        | 1.35±0.03    | 0.75 | -23.9      | 18.82                                    | ...               | ...          | 1.71              |
| 21   | 0.14±0.01        | 1.0±0.20     | 0.38 | 9.6        | 16.92                                    | ...               | ...          | 2.47              |
| 227  | 0.25±0.00        | 2.39±0.05    | 0.73 | -41.3      | 18.00                                    | ...               | ...          | 1.79              |
| 373  | 0.27±0.01        | 0.61±0.03    | 0.26 | -17.3      | 16.63                                    | ...               | ...          | 2.53              |
| 552  | 0.44±0.01        | 2.36±0.05    | 0.82 | 77.2       | 18.57                                    | ...               | ...          | 1.81              |
| 730  | 0.58±0.01        | 0.48±0.02    | 0.47 | 28.2       | 19.03                                    | ...               | ...          | 2.11              |
| 840  | 0.14±0.00        | 2.38±0.09    | 0.49 | 17.4       | 16.63                                    | ...               | ...          | 2.14              |
| 856  | 0.17±0.00        | 3.63±0.10    | 0.71 | -17.8      | 17.63                                    | ...               | ...          | 1.82              |
| 999  | 0.20±0.00        | 1.28±0.03    | 0.68 | 64.3       | 16.86                                    | ...               | ...          | 1.47              |
| 1144 | 0.49±0.01        | 1.35±0.03    | 0.32 | -24.0      | 18.58                                    | ...               | ...          | 2.66              |
| 1129 | 0.32±0.01        | 0.17±0.04    | 0.69 | -8.7       | 18.81                                    | ...               | ...          | 2.77              |
| 1257 | 0.09±0.00        | 3.45±0.20    | 0.73 | -7.3       | 17.04                                    | ...               | ...          | 1.66              |
| 1394 | 0.30±0.00        | 1.15±0.03    | 0.57 | -83.4      | 18.16                                    | ...               | ...          | 2.14              |
| 1533 | 0.33±0.03        | 1.21±0.25    | 0.91 | -82.3      | 20.11                                    | ...               | ...          | 0.66              |
| 1666 | 0.61±0.01        | 0.57±0.01    | 0.63 | 5.7        | 18.35                                    | 1.76              | 0.35         | 2.36              |
| 1768 | 0.14±0.01        | 2.05±0.16    | 0.60 | -78.6      | 16.90                                    | ...               | ...          | 2.10              |
| 1826 | 0.35±0.03        | 3.95±0.28    | 0.69 | 15.2       | 19.30                                    | 1.993             | 0.40         | 1.93              |
| 1942 | 0.31±0.01        | 1.99±0.26    | 0.91 | -4.1       | 18.02                                    | ...               | ...          | 2.05              |
| 2066 | 0.21±0.01        | 1.62±0.17    | 0.70 | 46.6       | 17.71                                    | 2.91              | 0.35         | 2.02              |
| 2083 | 0.12±0.00        | 4.04±0.18    | 0.53 | -3.0       | 16.07                                    | ...               | ...          | 1.93              |
| 2049 | 0.17±0.02        | 2.45±0.50    | 0.54 | -75.3      | 17.61                                    | ...               | ...          | 2.44              |
| 2282 | 0.57±0.03        | 0.76±0.06    | 0.59 | 80.1       | 20.20                                    | ...               | ...          | 2.11              |
| 2411 | 0.54±0.01        | 0.56±0.03    | 0.74 | -21.9      | 19.67                                    | ...               | ...          | 2.18              |
| 2564 | 0.11±0.00        | 1.69±0.07    | 0.47 | -27.9      | 16.31                                    | ...               | ...          | 1.80              |
| 2734 | 0.21±0.01        | 1.60±0.21    | 0.77 | -14.5      | 18.54                                    | ...               | ...          | 2.11              |
| 2678 | 0.11±0.00        | 2.39±0.09    | 0.35 | -74.6      | 15.17                                    | ...               | ...          | 2.06              |
| 2764 | 0.29±0.01        | 1.01±0.09    | 0.84 | -52.7      | 18.85                                    | ...               | ...          | 1.98              |
| 2902 | 0.22±0.01        | 1.88±0.18    | 0.50 | -15.7      | 18.46                                    | ...               | ...          | 2.02              |
| 2837 | 0.35±0.00        | 0.35±0.02    | 0.42 | 12.3       | 17.92                                    | 1.79              | 0.30         | 1.72              |
| 2965 | 0.15±0.00        | 1.70±0.11    | 0.62 | -57.9      | 16.74                                    | ...               | ...          | 3.03              |
| 3036 | 0.20±0.00        | 2.15±0.10    | 0.50 | -31.9      | 17.41                                    | ...               | ...          | 1.66              |
| 3126 | 0.36±0.01        | 1.27±0.07    | 0.57 | 62.4       | 19.35                                    | ...               | ...          | 1.84              |
| 3250 | 0.34±0.01        | 0.34±0.04    | 0.27 | 27.9       | 17.71                                    | ...               | ...          | 2.10              |
| 3422 | 0.35±0.02        | 0.50±0.00    | 0.37 | -64.4      | 18.13                                    | ...               | ...          | 2.16              |
| 3387 | 0.05±0.00        | 2.50±0.00    | 0.63 | -57.8      | 15.65                                    | ...               | ...          | 1.76              |
| 3582 | 0.27±0.02        | 1.92±0.37    | 0.77 | 74.6       | 19.33                                    | ...               | ...          | 2.34              |
| 3629 | 0.19±0.00        | 1.40±0.04    | 0.70 | 47.5       | 16.94                                    | ...               | ...          | 2.16              |
| 3818 | 0.40±0.00        | 2.07±0.03    | 0.79 | -21.4      | 18.98                                    | ...               | ...          | 1.62              |
| 3766 | 0.28±0.00        | 1.79±0.06    | 0.77 | -40.1      | 18.23                                    | ...               | ...          | 2.12              |
| 3822 | 0.21±0.01        | 2.33±0.23    | 0.84 | -45.3      | 19.04                                    | ...               | ...          | 2.33              |
| 3970 | 0.26±0.02        | 3.67±0.36    | 0.59 | -5.1       | 18.60                                    | ...               | ...          | 2.17              |
| 4121 | 0.06±0.00        | 2.20±0.00    | 0.34 | -74.3      | 14.17                                    | ...               | ...          | 4.38              |
| 4033 | 0.54±0.01        | 1.28±0.02    | 0.54 | -2.6       | 18.65                                    | ...               | ...          | 1.92              |
| 4239 | 0.38±0.02        | 1.20±0.09    | 0.52 | -42.5      | 19.05                                    | ...               | ...          | 1.87              |

Notes. (a) The values of the errors on  $R_e$  and Sersic  $n$  are representative of the  $1\sigma$  model errors from GALFIT (see Buitrago et al. 2008). This does not take into account many possible sources of error that may bias these measurements, including magnitude of galaxy, concentration of its light profile, etc. The uncertainty in these structural parameters increase by on order of 10 percent for  $R_e$  and 20 percent for  $n$  due to changes in the PSF across the NICMOS NIC3 field of view. Also listed is the fitted axis ratios for these galaxies (b/a), and position angles (P.A.). The effective surface brightness ( $\mu_{\text{eff}}$ ) is listed, as is the spectroscopic redshift ( $z_{\text{spec}}$ ), if available. The value of ‘sep’ is the difference between the position of an object and the identification of the spectroscopic target, in arcsec. Finally, the calculated photometric redshift,  $z_{\text{phot}}$ , is shown.

Scoville, N. et al. 2007, ApJS, 172, 1  
Thompson, R. et al. 1999, ApJ, 523, 100  
Thompson, R. et al. 2005, AJ, 130, 1  
Trujillo, I., Conselice, C.J., Bundy, K., Cooper, M.C., Eisenhardt, P., Ellis, R.S. 2007, MNRAS, 382, 109  
Steidel, C.C., & Hamilton, D. 1992, AJ, 104, 941  
van Dokkum, P.G., et al. 2009, PASP, 121, 2  
Vanzella, F., et al. 2008, A&A, 478, 83

Wang, W.-H. et al. 2010, ApJS, 187, 251  
Williams, R., et al. 1996, AJ, 112, 1335  
Wirth, G., et al. 2004, AJ, 127, 3121  
Wuyts, S. et al. 2008, ApJ 689, 653  
Yan, H., et al. 2004, ApJ, 616, 63  
Yan, H., et al. 2005, ApJ, 634, 109

**Table 6.** Structural parameters for galaxies with  $M_* > 10^{11} M_\odot$  within the GOODS-S field.

| ID   | $R_e$ (arcsec) | Sersic $n$ | b/a  | P.A. (deg) | $\mu_{\text{eff}}$ (mag arcsec $^{-2}$ ) | $z_{\text{spec}}$ | sep (arcsec) | $z_{\text{phot}}$ |
|------|----------------|------------|------|------------|--|-------------------|--------------|-------------------|
| 4299 | 0.31±0.01      | 0.65±0.06  | 0.46 | -8.0       | 18.57                                    | ...               | ...          | 0.31              |
| 4281 | 0.20±0.02      | 3.03±0.57  | 0.57 | -39.8      | 18.61                                    | ...               | ...          | 1.70              |
| 4348 | 0.34±0.02      | 1.78±0.17  | 0.58 | 85.3       | 19.84                                    | ...               | ...          | 0.76              |
| 4434 | 0.13±0.00      | 1.35±0.05  | 0.67 | -71.4      | 16.56                                    | 2.09              | 0.12         | 1.96              |
| 4399 | 0.08±0.01      | 3.40±1.00  | 0.70 | -69.9      | 17.70                                    | ...               | ...          | 2.31              |
| 4557 | 0.34±0.01      | 1.48±0.05  | 0.38 | 72.6       | 17.45                                    | ...               | ...          | 1.75              |
| 4754 | 0.38±0.01      | 0.75±0.03  | 0.44 | -37.6      | 18.68                                    | ...               | ...          | 2.21              |
| 4706 | 0.06±0.00      | 4.62±0.19  | 0.50 | -75.7      | 14.69                                    | 2.34              | 0.08         | 1.77              |
| 4882 | 0.10±0.00      | 2.25±0.08  | 0.65 | 2.8        | 16.44                                    | ...               | ...          | 1.41              |
| 4941 | 0.24±0.16      | 3.79±4.42  | 0.80 | -22.8      | 18.42                                    | ...               | ...          | 2.87              |
| 5171 | 0.10±0.00      | 3.36±0.28  | 0.66 | -32.0      | 16.50                                    | 2.40              | 0.21         | 2.58              |
| 5281 | 0.48±0.01      | 1.14±0.02  | 0.70 | 16.1       | 19.03                                    | ...               | ...          | 0.69              |
| 5445 | 0.42±0.03      | 1.06±0.08  | 0.52 | 61.7       | 19.36                                    | ...               | ...          | 2.39              |
| 5372 | 0.20±0.02      | 1.64±0.22  | 0.42 | -32.2      | 17.63                                    | ...               | ...          | 2.53              |
| 5533 | 0.09±0.00      | 3.20±0.32  | 0.63 | -33.5      | 16.29                                    | ...               | ...          | 2.37              |
| 5524 | 0.06±0.00      | 1.00±0.06  | 0.19 | -22.8      | 12.48                                    | ...               | ...          | 2.82              |
| 5764 | 0.16±0.01      | 2.88±0.15  | 0.64 | -27.6      | 16.95                                    | ...               | ...          | 2.34              |
| 5853 | 0.24±0.01      | 0.38±0.05  | 0.49 | -84.0      | 17.78                                    | 2.41              | 0.16         | 1.85              |
| 5933 | 0.27±0.00      | 1.08±0.05  | 0.92 | 64.0       | 18.84                                    | ...               | ...          | 2.48              |
| 6035 | 0.22±0.01      | 4.27±0.19  | 0.83 | -67.9      | 18.19                                    | ...               | ...          | 2.75              |
| 6114 | 0.11±0.00      | 3.90±0.12  | 0.72 | -68.4      | 16.00                                    | ...               | ...          | 1.55              |
| 6220 | 0.40±0.01      | 1.45±0.05  | 0.80 | -73.5      | 19.57                                    | ...               | ...          | 1.55              |
| 6352 | 0.50±0.03      | 2.59±0.11  | 0.51 | 65.7       | 19.54                                    | ...               | ...          | 2.56              |
| 6468 | 0.31±0.01      | 0.98±0.04  | 0.46 | -44.8      | 17.45                                    | ...               | ...          | 1.76              |
| 6584 | 0.34±0.01      | 1.10±0.03  | 0.22 | 68.8       | 17.16                                    | ...               | ...          | 1.66              |
| 6575 | 0.41±0.01      | 0.33±0.02  | 0.73 | -62.6      | 18.30                                    | ...               | ...          | 1.52              |
| 6876 | 0.29±0.01      | 0.47±0.04  | 0.35 | -82.7      | 17.18                                    | ...               | ...          | 1.35              |
| 7090 | 0.37±0.01      | 2.68±0.06  | 0.50 | -65.7      | 17.89                                    | ...               | ...          | 2.58              |
| 7155 | 0.10±0.01      | 4.52±0.35  | 0.51 | -66.8      | 15.67                                    | ...               | ...          | 0.49              |
| 7320 | 0.12±0.00      | 1.12±0.05  | 0.56 | -31.6      | 16.18                                    | ...               | ...          | 1.39              |
| 7425 | 0.16±0.00      | 2.13±0.06  | 0.45 | 66.4       | 16.48                                    | 1.31              | 0.2          | 1.40              |
| 7677 | 0.21±0.00      | 2.85±0.09  | 0.83 | 50.0       | 17.01                                    | 1.19              | 0.15         | 1.34              |
| 7970 | 0.37±0.01      | 0.56±0.02  | 0.84 | -79.4      | 18.73                                    | ...               | ...          | 1.72              |
| 8140 | 0.19±0.00      | 2.72±0.07  | 0.77 | -19.8      | 17.24                                    | 1.90              | 0.14         | 1.78              |
| 8213 | 0.15±0.00      | 1.69±0.07  | 0.63 | 53.8       | 16.56                                    | ...               | ...          | 0.70              |

Notes. (a) The values of the errors on  $R_e$  and Seric  $n$  are representative of the  $1 \sigma$  model errors from GALFIT (see Buitrago et al. 2008). This does not take into account many possible sources of error that may bias these measurements, including magnitude of galaxy, concentration of its light profile, etc. The uncertainty in these structural parameters increase by on order of 10 percent for  $R_e$  and 20 percent for  $n$  due to changes in the PSF across the NICMOS NIC3 field of view. Also listed is the fitted axis ratios for these galaxies (b/a), and position angles (P.A.). The effective surface brightness ( $\mu_{\text{eff}}$ ) is listed, as is the spectroscopic redshift ( $z_{\text{spec}}$ ), if available. The value of ‘sep’ is the difference between the position of an object and the identification of the spectroscopic target, in arcsec. Finally, the calculated photometric redshift,  $z_{\text{phot}}$ , is shown.